Seismic risk assessment at Emergency Limit Condition of urban neighbourhoods: application to the Eixample District of Barcelona

Final Thesis developed by:
Cara, Selma

Directed by:
Pelà, Luca
Aprile, Alessandra

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Department of Construction Engineering

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Abstract

The effects of an earthquakes on urban environments may produce uncountable losses to the society. Human lives and economic losses are the main consequences of this devastating and unpredictable natural hazard. The high concentration of population, buildings and infrastructures exposed, turns the territory into high-risk areas. Most of the earthquake casualties are due to buildings' collapse that produced 90% of direct deaths in the last catastrophic events.

The damage caused by the earthquakes depends not only on the intensity but also on the vulnerability of the structures. The assessment of the seismic vulnerability of buildings is one of the most relevant issues in earthquake engineering and in particular, in countries like Italy and Spain, where in most of the cases the heritage buildings were constructed without following any criteria of seismic protection.

The consequences of earthquakes are not only affected by the direct impact of the seismic event but also depend on the development of public policies of disaster prevention, as well as on the availability of effective emergency plans. The fundamental challenge is the assurance of structural safety in a sustainable built environment, with the preservation of the local culture and the collective memory. The urban centers continuously require maintenance and rehabilitation, but this activity also necessitates proper sources for their preservation.

The effects caused by any natural disaster may turn out to be so devastating to disable entire cities. The fear of not reaching the minimum safety standards has brought to the development of the concept of limit condition. The Emergency Limit Condition has been considered in this research defining a sub-system in the the "Antiga Esquerra de l'Eixample" neighborhood of Barcelona, Spain.

Barcelona is located in a low-to-moderate seismic risk region. L'Eixample district is characterized by unreinforced masonry buildings with rather high risk due to their vulnerability, its high density in buildings and population, as well as to the valuable exposition.

The general aim of this research is developing a model for the seismic vulnerability assessment at large-scale of urban systems. This estimation can be used to assess the damage caused by an earthquake scenario, in order to contribute to the post-seismic assessment of the loss distribution in an urban area. The objective is the identification of the most vulnerable buildings, which could benefit from being strengthened in order to preserve the functionality of the urban system as well as its resiliency. GNDT II methodology has been considered, with also some necessary improvements to its original format, in order to perform a reliable tool to assess the vulnerability of different construction systems.

To have a global overview of the results of the analysis at the urban scale, this research considers the use of GIS (Geographic Information System) software. This tool allows the effective storage, analysis and management of input data and provides plots of maps yielding the urban response to different post-earthquake scenarios. These maps of georeferenced scenarios are useful to detect and highlight the weak points of the complex urban network in order to plan suitable strategies to improve the resiliency of the city.

The preliminary results obtained in this research for the neighbourhood of the Antiga Esquerra de l’Eixample of Barcelona seem promising. The proposed methodology could be considered in future works dealing with the assessment of the seismic hazard and resiliency of complex urban centers.

Resumen

Los efectos de un terremoto en los entornos urbanos podrían llegar a generar innumerables perdidas sobre la sociedad, vidas humanas y perdidas económicas son las principales consecuencias que conlleva este impredecible riesgo natural. La elevada concentración de población, edificios e infraestructura expuesta, convierte a estos territorios en zonas de alto riesgo, donde la mayoría de las víctimas fatales se deben al colapso de los edificios alcanzando el 90% de las muertes directas en los últimos eventos catastróficos.

El daño causado por los terremotos, no depende solo de la intensidad de estos, si no también de la vulnerabilidad de las estructuras. La evaluación de la vulnerabilidad sísmica de los edificios es actualmente uno de los temas más relevantes en el ámbito de la ingeniería sísmica y en particularmente desarrollado en países como Italia y España, donde se concentran una gran cantidad de edificios con valor histórico-patrimonial que fueron construidos sin ningún criterio de diseño antisísmico.

Los efectos causados por cualquier desastre natural podrían llegar a ser tan devastadores hasta el punto de deshabilitar ciudades enteras, el temor de no alcanzar los mínimos estándares de emergencia, ha gatillado el desarrollo del concepto de condición límite. La Condición Límite de Emergencia ha sido considerada en esta investigación definiendo un sub-sistema en un barrio de la "Antiga Esquerra de l'Eixample" en Barcelona, España.

El territorio de Barcelona puede considerarse como una región de baja a moderada sismicidad. El distrito de L'Eixample, es caracterizado por sus edificios de mampostería no reforzada lo que supone un elevado nivel de riesgo sísmico debido a su vulnerabilidad, la alta densidad de edificios y su nivel de exposición.

El objetivo general de esta investigación es desarrollar un modelo para la evaluación de la vulnerabilidad sísmica a escala urbana. Estimación que puede ser posteriormente utilizada para la evaluación del daño causado en un escenario sísmico, con la finalidad de contribuir con un escenario general de la distribución de perdidas post-terremoto. El objetivo de esta etapa, es la identificación de los edificios más vulnerables, los cuales podrían ser beneficiados con el

reforzamiento de su estructura con el fin de preservar la funcionalidad del sistema urbano así como su resiliencia. La metodología GNDT-II ha sido considerada, junto a otros maneras mejoradas del método original, con el fin de realizar una herramienta confiable para el análisis de la vulnerabilidad en diferentes sistemas constructivos.

Para tener una visión general de los resultados del análisis a escala urbana, esta investigación considera el uso de *software* SIG (Sistemas de Información Geográfica). Esta herramienta permite un efectivo almacenamiento, análisis y manipulación de la información de entrada y proporciona la posibilidad de creación de mapas de riesgo y rendimiento de la respuesta urbana en diferentes escenarios. Estos mapas de escenarios georreferenciados son útiles para detectar y remarcar los puntos débiles en una configuración urbana compleja con el fin de planificar estrategias adecuadas para la mejora de la resiliencia de las ciudad.

Los resultados preliminares obtenidos en esta investigación para el barrio de la Antiga Esquerra de l’Eixample en Barcelona parecen prometedores. La metodología propuesta podría ser considerada en trabajos futuros abordando nuevos desafíos en el campo de la evaluación del riesgo sísmico y la resiliencia en centros urbanos.

Sommario

Gli effetti di un terremoto sull'ambiente costruito possono arrivare a produrre perdite innumerevoli nella società. Le perdite umane ed economiche sono le principali conseguenze di questo pericolo devastante e imprevedibile. L'alta densità di popolazione, gli edifici e le infrastrutture esposte convertono il territorio in zone di alto rischio. Molti degli effetti dei terremoti sono dovuti al collasso degli edifici, che hanno prodotto il 90% di morti dirette nei ultimi eventi catastrofici.

Il danno causato da un terremoto dipende non solo dall'intensità ma anche dalla vulnerabilità delle strutture. La valutazione della vulnerabilità sismica degli edifici è uno dei problemi più rilevanti in Ingegneria Sismica e in particolare, in paesi come l'Italia e la Spagna, dove nella maggior parte dei casi il patrimonio culturale è stato costruito senza seguire alcun criterio di protezione sismica.

Le conseguenze dei terremoti non solo dipendono dagli impatti diretti di un evento sismico, ma anche dallo sviluppo di politiche di prevenzione di danno e dalla disponibilità di piani effettivi d'emergenza. La sfida principale è la garanzia della sicurezza strutturale in un ambiente costruito sostenibile, assieme ad una cultura di prevenzione della memoria locale e collettiva. I centri urbani continuamente richiedono manutenzione e ristrutturazione, sebbene queste attività abbiano bisogno di risorse opportune per il loro svolgimento.

Gli effetti causati dai fenomeni naturali possono diventare devastanti fino al punto di disabilitare intere città. La paura da non raggiungere gli standard minimi di sicurezza ha portato allo sviluppo del concetto di condizione limite urbana. La Condizione Limite di Emergenza è stata considerata in questa ricerca per il quartiere dell'Antiga Esquerra de l'Eixample di Barcellona, in Spagna.

Barcellona è situata in una regione di bassa-media sismicità. Il distretto dell'Eixample è caratterizzato da edifici di muratura non rinforzata, avendo così un alto rischio dovuto alla loro vulnerabilità, densità alta degli edifici e della popolazione, ed anche al loro valore di esposizione.

L’obiettivo principale di questa ricerca è sviluppare un modello di valutazione di vulnerabilità sismica a grande scala di sistemi urbani. Quest’analisi può essere usata per valutare il danno causato da un possibile scenario di terremoto, così da contribuire alla valutazione post-sismica della distribuzione delle perdite nell’area urbana. L’obiettivo è l’individuazione degli edifici più vulnerabili, che possono migliorare il loro comportamento sismico una volta che vengano realizzati interventi atti a preservare la funzionalità degli insiemi urbani e la loro resilienza. E’ stato usato il metodo GNDT II, con alcuni miglioramenti rispetto al suo formato originale, in modo da sviluppare uno strumento affidabile per valutare la vulnerabilità sismica di differenti sistemi costruttivi.

Per avere una panoramica globale dei risultati dell’analisi in scala urbana, questa ricerca considera l’uso di un programma GIS (Geographic information system). Questo strumento permette un’analisi effettiva così come la gestione dei dati di input e fornisce allo stesso tempo la rappresentazione grafica di mappe di risposta per differenti scenari post-terremoto. Queste mappe di scenari geo-referenziati sono utili per rilevare ed evidenziare i punti più deboli di tutta la rete urbana e per pianificare poi strategie opportune tali da migliorare la resilienza della città.

I risultati preliminari ottenuti da questo studio per il quartiere dell’Antiga Esquerra de l’Eixample di Barcellona sembrano promettenti. La metodologia proposta può essere considerata nell’ambito di lavori futuri sulla valutazione della vulnerabilità sismica e la resilienza di centri urbani complessi.

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Chapter 1

INTRODUCTION

1.1 MOTIVATION FOR THE PRESENT RESEARCH

During the last decades, enormous losses were registered related to a large number of natural disasters in the world. Particularly, numerous seismic events occurred and produced huge economic and social losses with a consequent territorial impact, both on areas directly hit by earthquakes and on areas related economically with the damaged area. A seismic event can produce remarkable impact on a city, such as the delay in the emergency response and the consequent inoperability of lifelines. Seismic events can have a huge negative impact on the national economy too. An example of this impact is the case of L'Aquila earthquake on 6 April 2009. The effects of the earthquake were disastrous (see Figure 1.1).

Figure 1.1 *Disaster effects on L'Aquila city due to the earthquake on 6 April, 2009 (Google image).*

In this contest, a seismic risk assessment model is necessary to prevent consequent economic and social losses. Risk mitigation is considered essential for urban management. The most common approach to seismic risk mitigation is characterized only by strategies reducing single buildings' vulnerability, through structural interventions, and it does not consider the possibility to intervene at urban scale, reducing urban seismic vulnerability.

In this research, the attention has been relocated from the analysis of the single building to that of the complex urban system. Due to the complex construction process of the urban mesh, buildings do not constitute independent units and do not have independent structural behaviors. It is important to study the relationship with the other buildings by extending the research at a larger scale.

This thesis deals with the urban seismic vulnerability, and introduces the concept of urban resilience, as the capacity of a system to adapt itself to new, generally negative, conditions, in order to re-establish its normal original conditions. Each city can express resilience, and the identification of its most influent elements is the aim of the research.

The main purpose of this investigation is to define a methodology to evaluate the seismic vulnerability of urban centers. Another principal aim is the determination of the damage scenarios under different seismic intensities in order to define the decisions in the post-earthquake emergency, such as strategies to reduce seismic risk and territorial planning.

An application of the proposed methodology is presented having chosen the District of Eixample, Barcelona (Spain). There are defined the functions of the urban neighbourhood and consequently the correlations with other critic levels of functionality.

1.2 AIM AND OBJECTIVES

1.2.1 General objectives

This research was developed at the Department of Civil and Environmental Engineering of the Polytechnic University of Catalonia (UPC-BarcelonaTech) in collaboration with the University of Ferrara. The study has the main objective of implementing a model to asses seismic risk at the urban scale.

It has been recognized that the global activity of a town can be compared to the activity of a network system, where each part, working at local level, contributes at global level. From this point of view, it becomes evident that the physical damages are not only components of the global damage. Moreover, it has been observed that the earthquake effects are not limited to the physical damages, but they do have some consequences on economic, social and political activities. They also have a strong role onto the city's capacity to react. That being so, risk prevention must be characterized by a new approach going over the building structural adjustment.

It is important to choose an appropriate method, which fulfil the objectives of this research. Detailed approaches are suitable when dealing with single buildings. Other approaches, less accurate but simpler and quicker, are more efficient for larger scale analysis. The use of an exhaustive method leads to very reliable results through an in-depth analysis of the structure. However, increasing the number of buildings and enlarging the area under assessment, the amount of time required for the analysis drastically increase, so the use of simpler and less onerous approaches becomes more practical. For that reason, vulnerability assessment methods at urban scale should be based on parameters of empirical nature, but whose effects were calibrated carefully on the basis of the recorded effects of past earthquakes. In one hand, the methodology should be easy and practical to use, but in the other hand should provide reliable results.

The adopted methodology GNDT II is based on the consideration of the practical and economic impossibility to ensure a maximum level of protection of the entire urban system. The strategy adopted is aimed to define planning policies avoiding a sudden collapse of the system. The approach demonstrates the ability to configure different subsystems of urban resistance.

GNDT II method defines the vulnerability indexes for Emergency Limit Condition for urban sub-systems and then it calculated their vulnerability. The fragility curves of the sub-system are then determined to evaluate the extent of the different levels of damage. Consequently, it is possible to define a seismic risk scenario, and consequently it is possible to draw an evaluation of costs. The obtained results may constitute a preliminary source of data to establish an intervention plan in order to recover the initial living standards after the event.

1.2.2 Specific objectives

The following specific objectives are pursued in this study:

- Carry out an urban planning investigation of the Eixample District of Barcelona by studying the urban mesh and identifying the principal lifelines of the neighborhood.
- Identification in the Eixample District of the interfering and strategic buildings located along the important communication axes from Hospital Clinic to Aragón Street, according to Emergency Limit Condition (ELC).
- Research and collect data on historical original documents about interfering and strategic buildings.
- Identification of constructive typologies, analysis of the materials' characteristics and the peculiarities of each of them.
- Convert all the data collected in a digital format (all the floor plans from paper format to AutoCAD) and then reconstruct the missing information.
- Carry out a research about the state of the art and evaluate which methodology is suitable in this case of study.

- Describe GNDT II methodology explaining the reason of choosing this model, as well as the points that could be improved by further studies.
- Consider an improvement of the GNDT-II methodology of study based on the concept of the Ellipse of vulnerability.
- Find a correlation to determine the vulnerability of the buildings of the neighbourhood on the basis of the previous evaluation of their vulnerability indexes.
- Evaluate the damage grade by using a correlation with the vulnerability.
- Construct the fragility curves from the damage grade calculated before.
- Calculate the probabilities corresponding to different limit states (collapse building, death and injured people, unusable buildings) in order to evaluate the consequent economical losses.
- Develop a GIS-based database in order to gather all the information and provide an effective view of the vital points of the city object of study.
- Simulate different seismic scenarios using a spatial analysis ArcGIS.

1.3 OUTLINE OF THE THESIS

This dissertation is divided into six chapters. The Chapter 1 presents an overall introduction to the research and deals with the aims and objectives of the thesis.

The Chapter 2 deals with the "*state of the art*" of seismic vulnerability assessment methods, giving an overview and summarizing current and past literature, divided by level of accuracy. In addition, planning politics of mitigation of risks and limit conditions for settlements are described. More in specific, the Emergency Limit Condition is discussed, as proposed by the "Protezione Civile", the Italian national body that deals with prediction, prevention and management of exceptional events.

Chapter 3 describes the methodology adopted and all the proposed developments of the standard GNDT-II methodology, explaining how they were formulated and how they can improve the evaluation method by making it more detailed and complete. A deeper analysis of the masonry buildings is then carried out, considering the effects of the aggregates.

Chapter 4 includes the description of the case study, which is of the Eixample District of Barcelona (Spain), along with the different aspects of buildings’ construction typologies, the seismology of the area and the Emergency Limit Condition (ELC).

Chapter 5 shows the evaluation of the results obtained, first in a numerical way and then through visual maps produced by using the GIS software.

Finally, Chapter 6 presents the summary and principal outcomes of the current research as well as suggestions for future works.

Chapter 2

STATE OF THE ART

2.1 SEISMIC RISK

It is defined seismic risk (R) the estimation of total loss (human lives, economic property, cultural values, buildings) that a seismic event can produce in a determined area.

In other words, the risk is the probability of being reached a prefixed level of loss at a certain interval of time T. This loss is identified as the cost that should be supported to return the damaged system at the condition before the seismic event. The evaluation of an area where the condition of seismic risk occurs is related as an evaluation of three fundamental parameters: Hazard, Vulnerability, and Exposure (see Figure 2.1).

Seismic Hazard (H) depends on the characteristics of a seismic event and geological characteristics of the area where the event is manifested.

The Vulnerability (V) is defined as the susceptibility of a structure to submit damage due to a certain earthquake. This damage can bring immediate decline of its functionality and, even worst, the total irrevocability.

Finally, the Exposure (E) is related to the nature, the quantity and value of properties and activities present at the area that can be influenced directly or indirectly by a seismic event (buildings, infrastructures, population density).

Conceptually, seismic risk can be express as a relation shown in Equation 2.1 (Coburn AW 2002):

Seismic Risk = Hazard x Vulnerability x Exposure

$$R = H \otimes V \otimes E \tag{2. 1}$$

In a more rigorous way, seismic risk of a building can be represented by its probability of collapse at a temporal interval of interest.

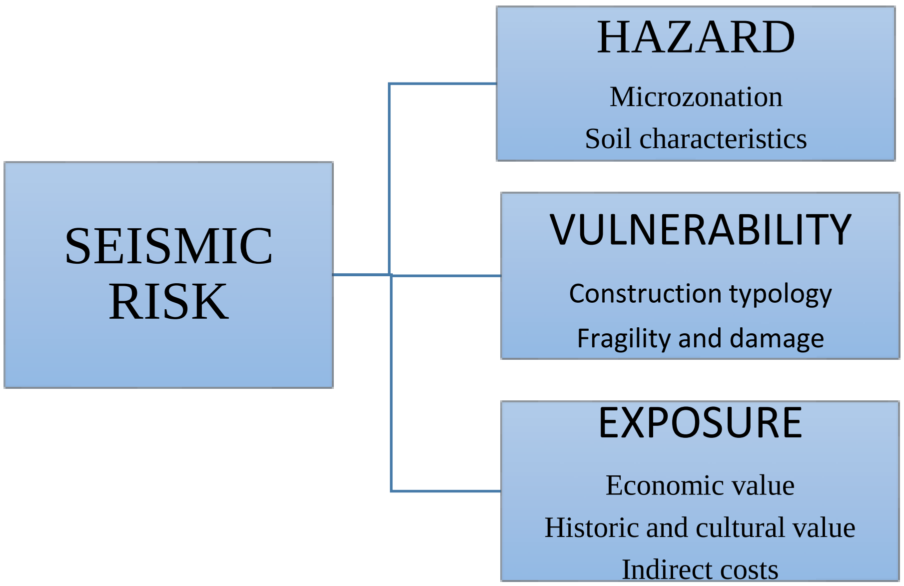


Figure 2.1 Seismic risk and its components.

2.1.1 Evaluation of the seismic hazard

Seismic hazard represents a measure of destructive potential of the earthquake and it is related to typically aleatory factors, which are the frequency with which this phenomenon is repeated, as well as the geologic characteristics of the area where the events appear. The knowledge of the seismic hazard of a site turns into an instrument of severity grade prediction of the expected earthquake. This severity is measured using instrumental scale or macro-seismic scale. The first one is based on parameters related to ground motion, like the Peak Ground Acceleration (PGA), the Local Magnitude or the Richter Magnitude. These are the mostly used mechanical quantities in the engineering field and they are not related to the past seismic events. The macro-seismic scale, on the other hand, is less accurate but has the advantage of offering an estimate of mean intensity in a hit zone, which is based directly on observed damage and can be associated with the past earthquakes.

The evaluation approach can be of two types: deterministic or probabilistic. The deterministic method is based on the study of the observed damage of the seismic events that interested a certain area, reconstructing the damage scenario to determine the frequency with which it was repeated by time having the same intensity. This approach was used widely in the past. However, the probabilistic method is preferred at the analysis level. This method is based on the information obtained from the seismic history of a site and determines the probability that at a certain area and at a certain interval of time an earthquake can occurr by exceeding a threshold of intensity or magnitude of PGA of our interest. The Figure 2.2 shows the global seismic hazard map nowadays.

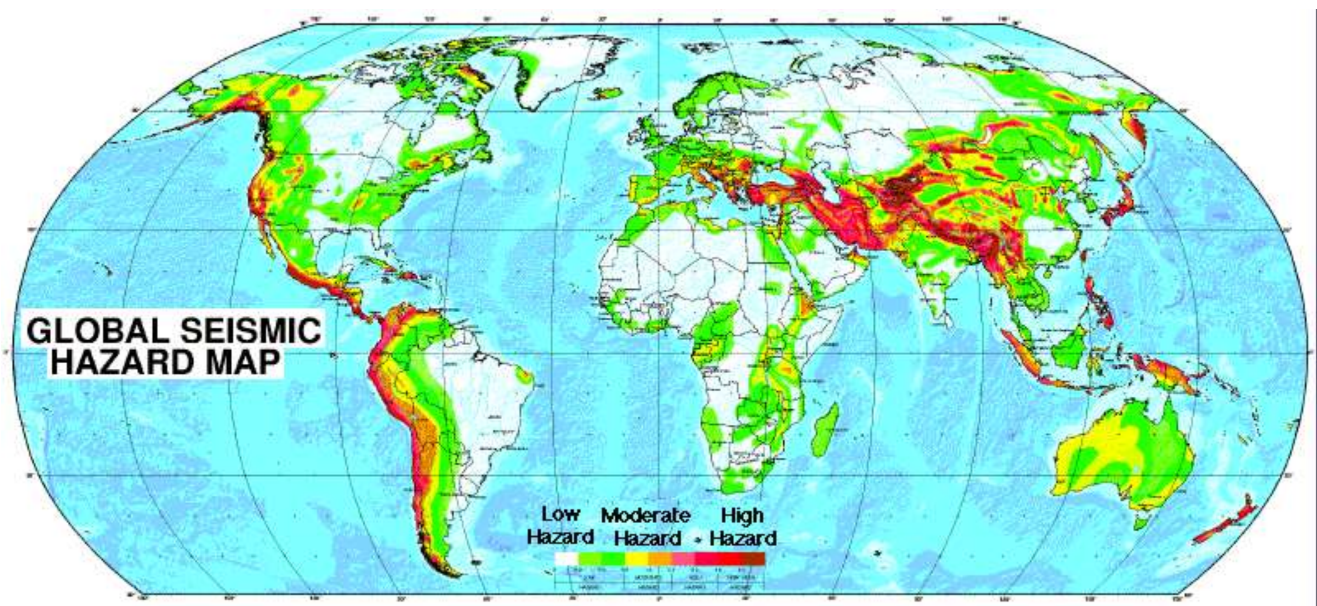


Figure 2.2 Global seismic hazard map (Map by United States Geological Survey).

2.1.2 Evaluation of the exposure

Exposure (E) of an area is referred to the nature, the quality and quantity of properties exposed at the risk. Therefore, exposure is defined as a quantification of construction (buildings, infrastructures, etc.) and number of persons that are presumed of being involved after a seismic event, as well as the evaluation of their capacity of reaction. The exposure is composed by a functional component and user's component. To describe completely the total elements defining the risk that a community is exposed, it is necessary to analyze: the distribution, the structure and the social-economic condition of habitants; the quantity and functions of residential, public and productive building heritage; infrastructural systems; all the economic activities and the relationship of the area with the adjacent others. The Figure 2.3 shows a global level of exposure map to natural hazards.

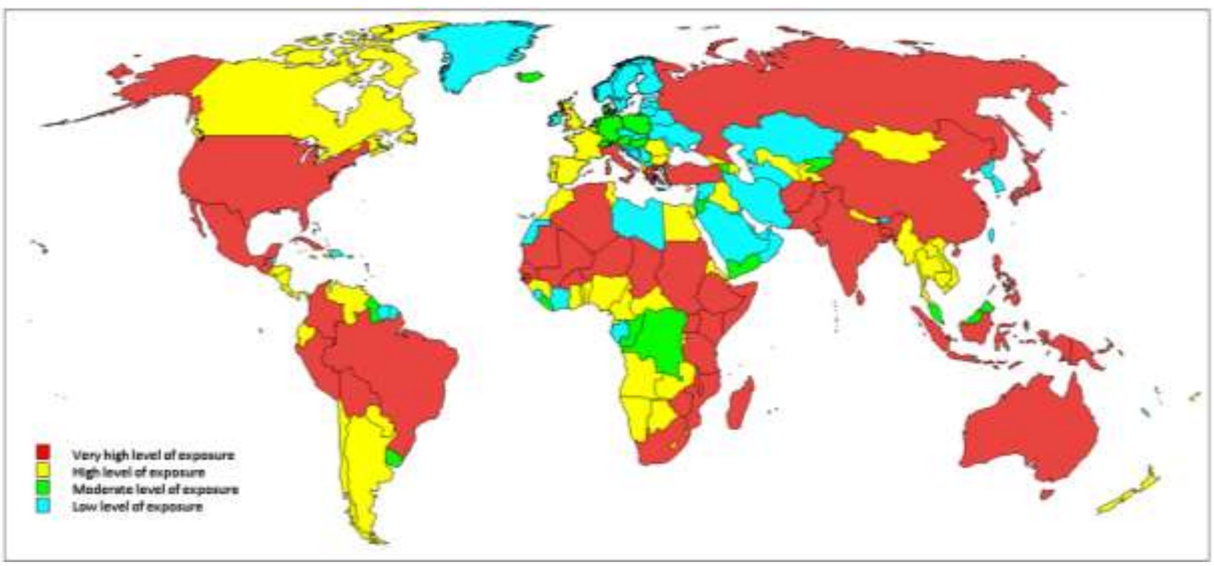


Figure 2.3 Map estimating the global level of exposure to natural hazards (Gilles 2003).

2.1.3 Evaluation of the seismic vulnerability

Seismic vulnerability of a building is the measurement of the susceptibility to be subjected to damage because of an earthquake of assigned characteristics. The first problem to face with is how to identify these characteristics. About seismic action, there are different possibilities and one of these is macro-seismic intensity, which represents a convenient parameter to be used because of the direct correlation between intensity scales with damages caused by an earthquake. The disadvantage is the difficulty to correlate this parameter with spectral values, which permits to define the hazard. The damage generally is expressed in terms of economic costs or through indexes. The Figure 2.4 shows a level risk map according to an economic approach to vulnerability. In the last 30 years, different methodologies were developed to evaluate the vulnerability. A classification is shown in the following section.

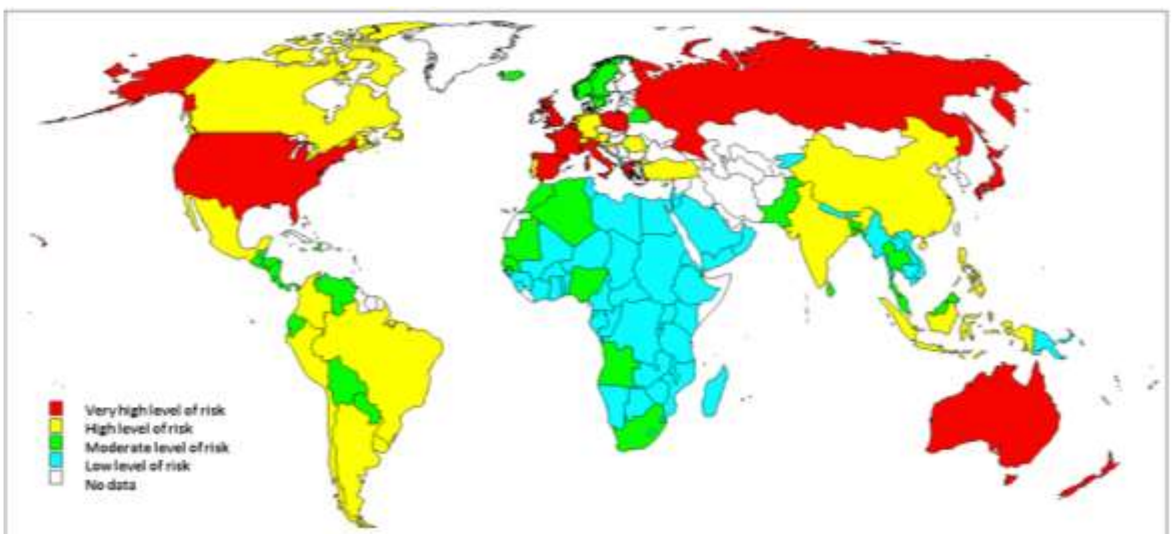


Figure 2.4 Level risk map according to an economic approach to vulnerability (Gilles 2003).

2.2 VULNERABILITY ASSESMENT METHODS

Developing a model able to estimate the losses caused by an earthquake seems to be very important as it permits to analyze the impact of future earthquakes and so to organize measures of risk mitigation. Possible measures are territorial planning, design of new seismic protection for structures, or in general to transform a city into a “smart city” able to guarantee the security and well-being of habitants exposed to different risks.

Using models of loss, the surplus costs to support the phase of construction and reconstruction, necessary to guarantee a bigger seismic resistance, can be compared with the potential loss, which can be successively avoided. These models can be used to realize cost-benefit analysis applied at different cases evaluating the different impacts in economic terms. To realize a model, which estimates seismic losses of a city it is necessary to have an available database which includes information about historic earthquake data, soil conditions, seismic vulnerability of the zone, seismic amplification, etc.

A significant element of a loss model is the method used to evaluate the vulnerability of a construction. In fact, one of the principal objectives is to correlate structural vulnerability with seismic hazard of a specific zone to determine and quantify the propensity of damage after a seismic event and eventual economic losses caused by the damage at a certain period. It is possible to realize a comparison between the costs of retrofit and repair or demolition and reconstruction. This is measured by the effect of damage that the structure can suffer after an earthquake of determined intensity. Quantify the seismic vulnerability of a building means to find a correlation between a representative parameter of soil motion, (macro-seismic intensity, PGA, etc.) and a representative parameter of damage.

There are different types of methods used to estimate the loss. Three categories, which can be classified, are the following (see Figure 2.5):

- Empirical methods.
- Analytical methods.

- Hybrid methods.

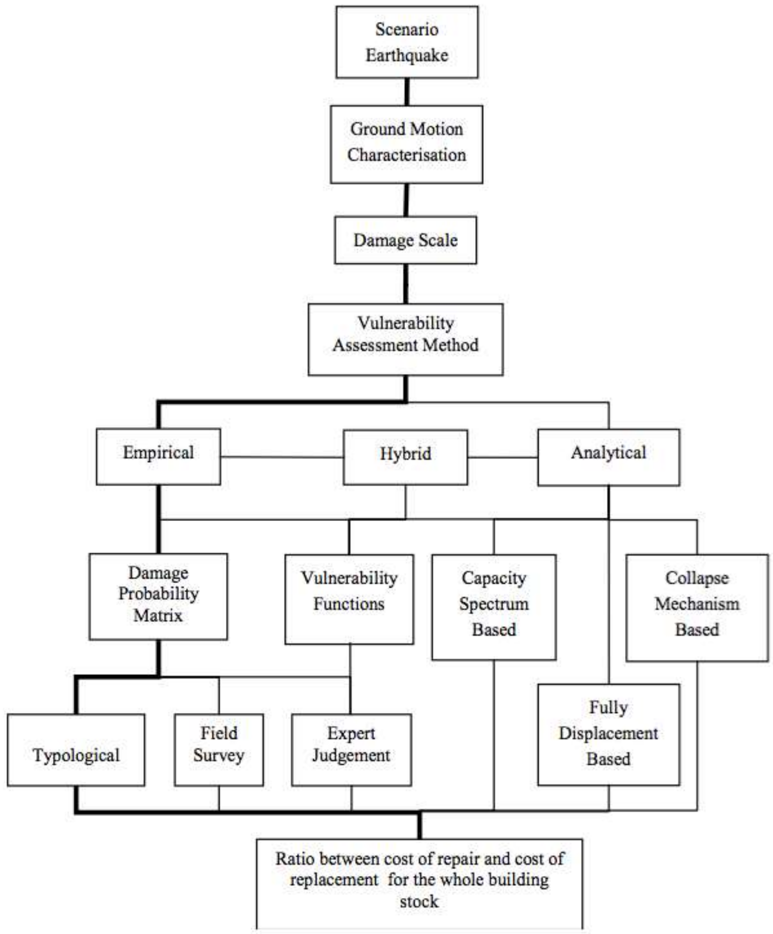


Figure 2.5 The components of the seismic risk assessment and different paths for the vulnerability assessment procedure (Calvi et al. 2006).

Traditionally, the evaluation of the damage of an event is defined through macro-seismic intensity of peak ground acceleration (PGA), and recent researches propose an approach based on a correlation between seismic vulnerability of buildings with response spectrum obtained by ground motion. Many models use for the evaluation of the vulnerability a discrete scale of damage. The most frequent are MSK scale (Medvedev & Sponheuer 1969), Mercalli scale (Wood & Neumann 1931) and EMS-98 scale (Grünthal 1998).

In empiric models of vulnerability, the scale of damage is used to produce post-earthquake damage statistics. Analytical models are related to the mechanical properties of a building (limit states), e.g. the displacement capacity of a storey.

The evolution of vulnerability models, both for single buildings and aggregates at urban scale (see Figure 2.6), is described in the following paragraphs together with the cases of applicability of each method. The following paragraphs also describe the state of art on urbanistic evaluation and interaction between the urban components.

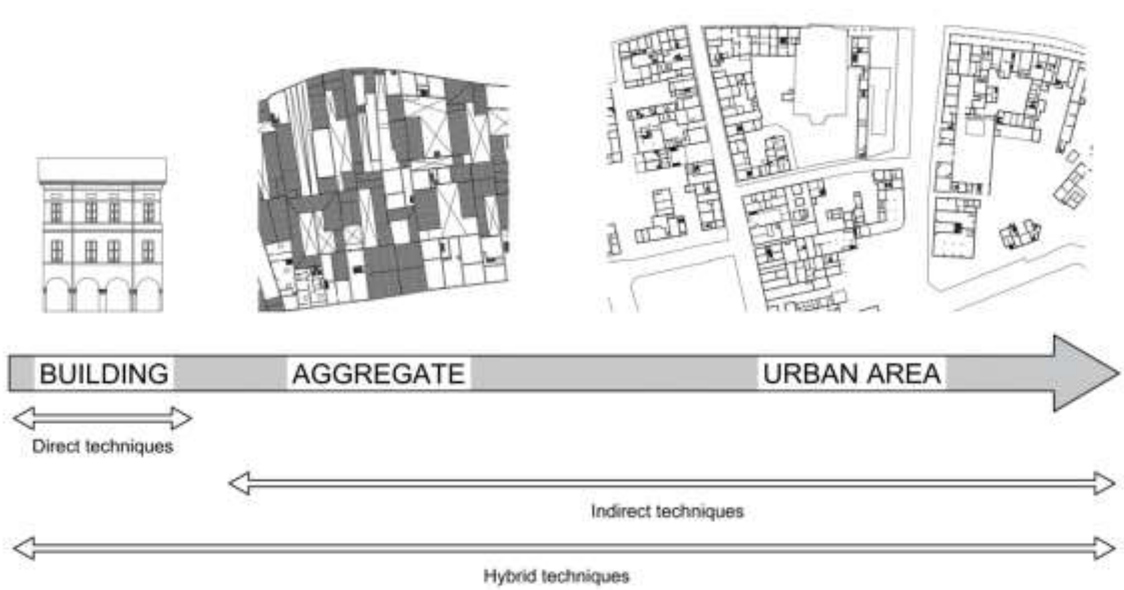


Figure 2.6 Vulnerability methods used at different scales (Basaglia 2015).

2.2.1 Empirical methods

The available empirical methods are:

- Damage Probability Matrix (DPM), which represent in a discrete form the probability of having a determinate damage level j due to an assigned macro-seismic intensity I,

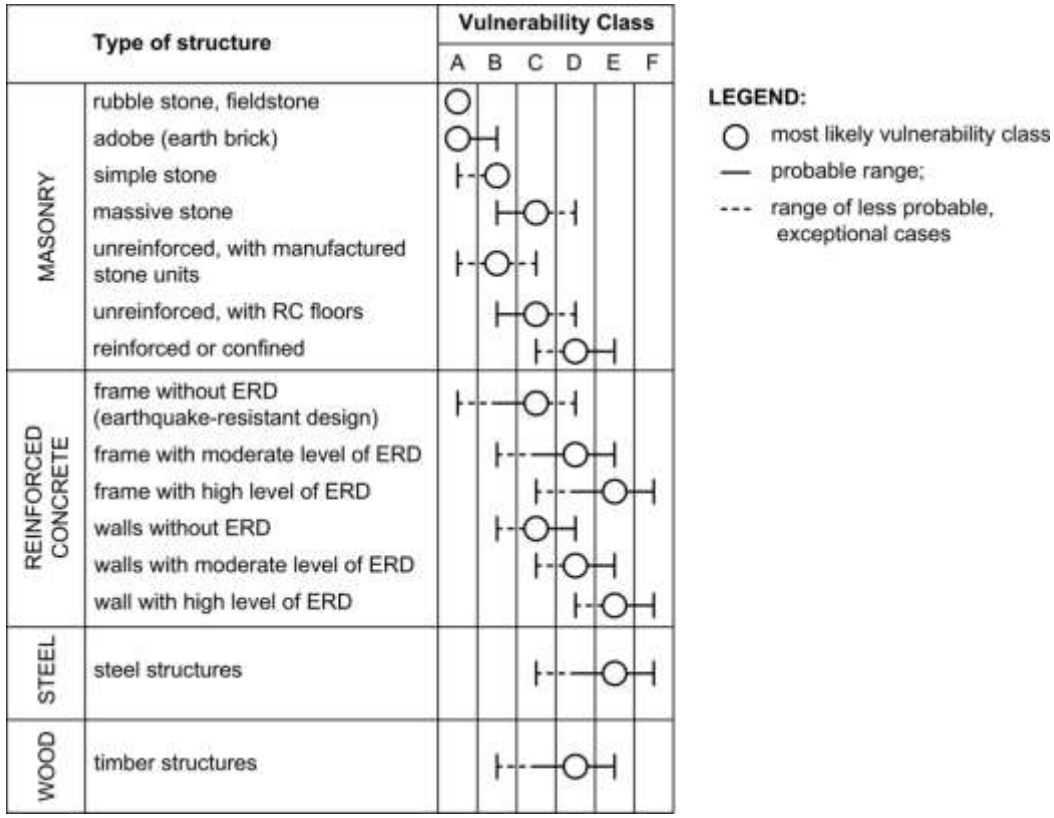
- Vulnerability function, which are continuous functions, expressing the probability of exceedance of a determinate damage level related to specific earthquake intensity.

Both methods are based on observed damage after an earthquake and on the relation damage-hazard. The first on proposing the use of damage probability matrix was Whitman (Whitman et al. 1974) after the earthquake of San Fernando in 1971. In Europe the first version was proposed by Braga (Braga et al. 1982) after the earthquake of Irpinia in 1980 introducing a binomial distribution to describe damage distribution for different vulnerability classes and different macro-seismic intensities.

The probability matrix based on expert opinion are introduced by ATC 13 (Applied Technology Council ATC 1985), estimating the damage factor (cost of restructuring and cost reconstruction expressed in percentage) as a function of macro-seismic intensity Mercalli-Modified I_{MM} for the range 6-12 and for 36 different building classes.

Recently a macro-seismic method has been proposed (Giovinazzi & Lagomarsino 2004) which brings on the definition of damage probability functions based on macro-seismic scale EMS-98 (Grünthal 1998). EMS-98 scale defines a qualitative relation between 5 damage levels and macro-seismic intensity level range 5-12, for 6 different vulnerability classes (from A to F). The European macro-seismic scale (EMS-98) provides the actual assignment of a building to a vulnerability class mainly by the structural typology with an uncertain margin, as shown in Table 2.1.

Table 2.1 Vulnerability classification according EMS-98.



In order to evaluate the influence of other parameters on the structural response to an earthquake of a determinate typology, the data of damage based on past seismic events have been interpreted statistically. In particular, different damage distributions have been obtained (D0, D1, D2, D3, D4, D5) for different categories of buildings having the same structural typology (see Figure 2.7, 2.8).

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage** **(slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction** **(very heavy structural damage)** Total or near total collapse.

Figure 2.7 Damage grade classification for masonry buildings (EMS-98).

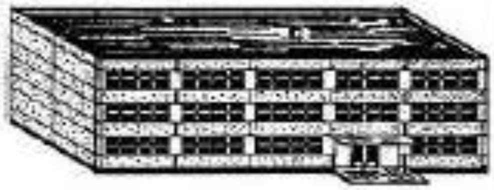
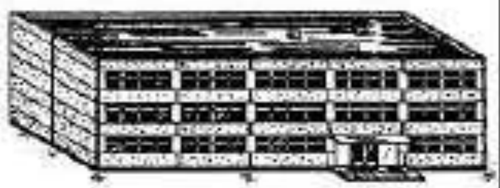
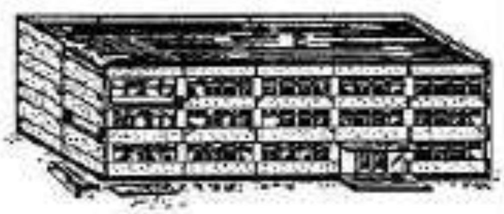
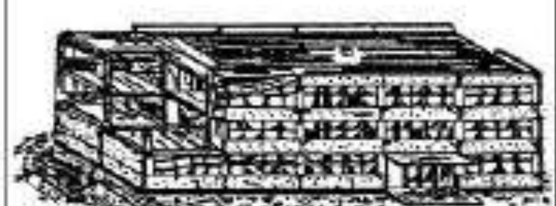
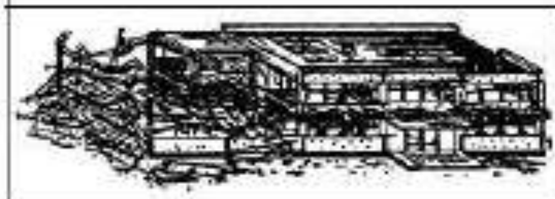
Classification of damage to buildings of reinforced concrete	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
	**Grade 2: Moderate damage** **(slight structural damage,** **moderate non-structural damage)** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of conrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
	**Grade 5: Destruction** **(very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

Figure 2.8 Damage grade classification for RC buildings (EMS-98).

Table 2.2 Damage models for different vulnerability classes according to EMS-98 scale.

Dk/I	*0*	*1*	*2*	*3*	*4*	*5*
V		Few A or B				
VI		Many A or B, Few C	Few A or B			
VII			Many B, Few C	Many A, Few B	Few A	
VIII			Many C, Few D	Many B, Few C	Many A, Few B	Few A
IX			Many D, Few E	Many C, Few D	Many B, Few C	Many A, Few B
X			Many E, Few F	Many D, Few E	Many C, Few D	Most A, Many B, Few C
XI			Many F	Many E, Few F	Most C Many D, Few E	Most B, Many C, Few D
XII						All A or B, Nearly All C, Most D or E or F

By analyzing the description of the intensities (see Table 2.2), it is recognizable that the EMS-98 presents some limitations, such as the *vagueness of adjectives* (such as “Few”, “Many”, “Most”) and the *lack of information* (for each class and intensity, the frequency of two damage grades at most is portrayed). The problem related to the uncomplete and *vagueness of adjectives* of the matrix was resolved by Giovinazzi and Lagormasino (Giovinazzi & Lagomarsino 2004) using the damage distribution β and Fuzzy-Set Theory. In order to associate a numerical value each of the three key adjectives of the scale (Few, Many, Most) has been initially related to a “*fuzzy set*” (varying in a range [0,100], for a detailed explanation of the fuzzy logic see (Zadeh L. A, 1965) using the “*fuzzy pseudo-partition*” method (Klir & Yuan 1995), as shown in Figure 2.9. The condition is that for each percentage the sum of the values (vertical axis) has be 1 (in analogy with the sum of all possible events’ probabilities). Later the sets “Nearly All” and “Nearly None” have been added: in this way extreme values 0 and 100 are no longer assigned to adjectives “Few” and “Most” (Bernardini et al. 2007, see Figure 2.10).

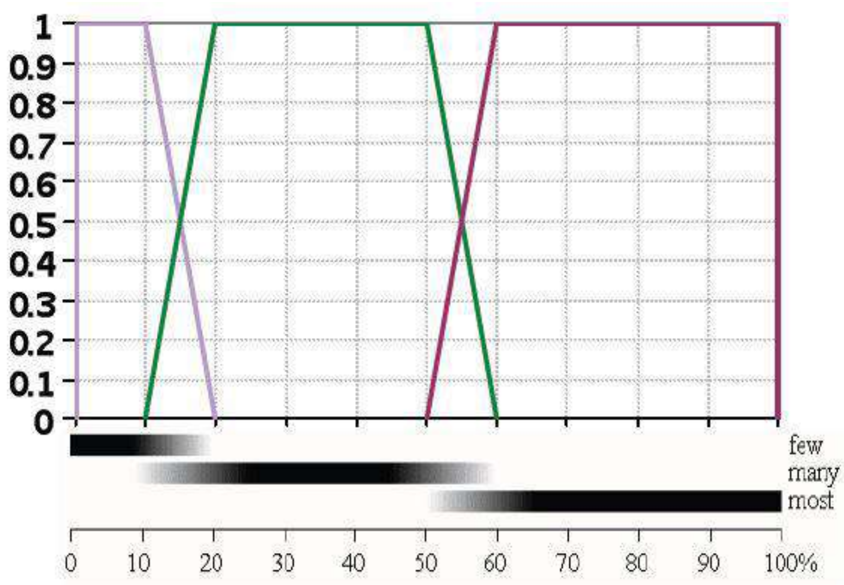


Figure 2.9 "Fuzzy pseudo partition" of numerical range 0-100 using 3 "fuzzy sets" (Klir & Yuan 1995).

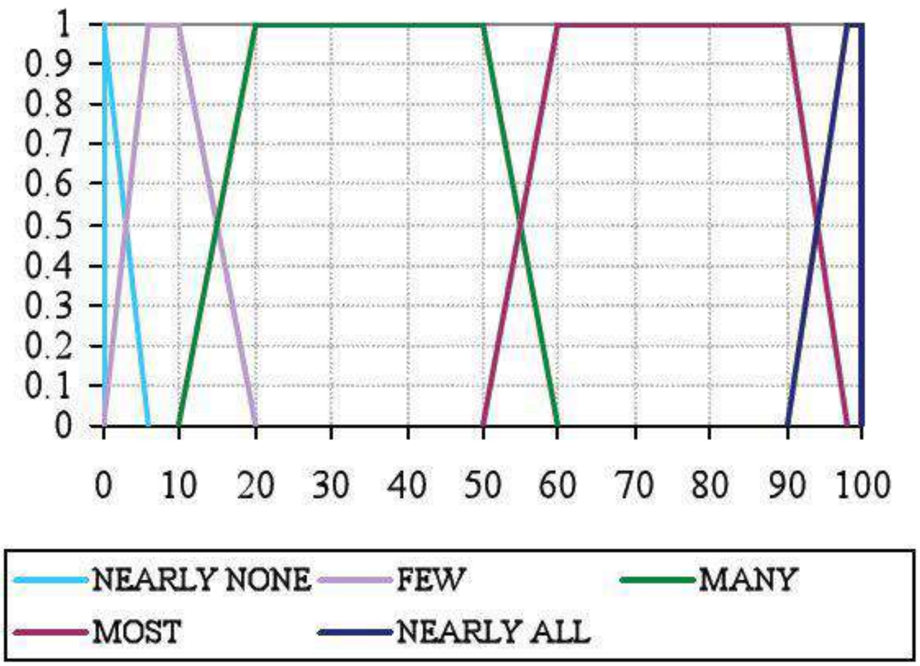


Figure 2.10 "Fuzzy pseudo partition" of numerical range 0-100 using 5 "fuzzy sets" (Bernardini et al. 2007)

Finally it was possible to complete every DPM for the EMS-98 scale, with damage frequencies for each intensity and vulnerability class (see Table 2.3).

Table 2.3 Language completion of EMS-98 scale.

Dk / I	*0*	*1*	*2*	*3*	*4*	*5*
CLASSE A						
V	*All-Few*	**Few**	None	None	None	None
VI	*Many + 7/3Few*	**Many**	**Few**	None	None	None
VII	*1/3Few*	*2Few*	*Many*	**Many**	**Few**	None
VIII	None	*1/3Few*	*2Few*	*Many*	**Many**	**Few**
IX	None	None	*1/3Few*	*3Few*	*Many*	**Many**
X	None	None	None	*5/6Few*	*2Few*	**Most**
XI	None	None	None	None	*5/6Few*	*Most + 2Few*
XII	None	None	None	None	None	**All**
CLASSE B						
V	*All-Few*	**Few**	None	None	None	None
VI	*Many + 7/3Few*	**Many**	**Few**	None	None	None
VII	*7/3Few*	*Many*	**Many**	**Few**	None	None
VIII	*1/3Few*	*2Few*	*Many*	**Many**	**Few**	None
IX	None	*1/3Few*	*2Few*	*Many*	**Many**	**Few**
X	None	None	*1/3Few*	*2Few*	*Many+ Few*	**Many**
XI	None	None	None	*Nearly Few*	*8/3Few*	**Most**
XII	None	None	None	None	None	**All**
CLASSE C						
V	*All*	None	None	None	None	None
VI	*All-Few*	**Few**	None	None	None	None
VII	*Many + 7/3Few*	*Many*	**Few**	None	None	None
VIII	*7/3Few*	*Many*	**Many**	**Few**	None	None
IX	*1/3Few*	*2Few*	*Many*	**Many**	**Few**	None
X	None	*1/3Few*	*2Few*	*Many*	**Many**	**Few**
XI	None	None	None	*4/3Few*	**Many+ 2Few**	**Many**
XII	None	None	None	None	*1/3Few*	**Nearly All**

CLASSE D						
V	*All*	None	None	None	None	None
VI	*All*	None	None	None	None	None
VII	*All-Few*	**Few**	None	None	None	None
VIII	*Many+ 7/3Few*	*Many*	**Few**	None	None	None
IX	*7/3Few*	*Many*	**Many**	**Few**	None	None
X	*1/3Few*	*2Few*	*Many*	**Many**	**Few**	None
XI	None	*1/3Few*	*2Few*	*Many*	**Many**	**Few**
XII	None	None	*1/3Few*	*1/2Few*	*2Few*	**Most**
CLASSE E						
V	*All*	None	None	None	None	None
VI	*All*	None	None	None	None	None
VII	*All*	None	None	None	None	None
VIII	*All-Few*	*Few*	None	None	None	None
IX	*Many+ 7/3Few*	*Many*	**Few**	None	None	None
X	*7/3Few*	*Many*	**Many**	**Few**	None	None
XI	*1/3Few*	*2Few*	*Many*	**Many**	**Few**	None
XII	None	*Nearly Few*	*2/3Few*	*Few*	*2Few*	**Most-Few**
CLASSE F						
V	*All*	None	None	None	None	None
VI	*All*	None	None	None	None	None
VII	*All*	None	None	None	None	None
VIII	*All*	None	None	None	None	None
IX	*All-Few*	**Few**	None	None	None	None
X	*Many+ 7/3Few*	*Many*	**Few**	None	None	None
XI	*7/3Few*	*Many*	**Many**	**Few**	None	None
XII	None	*1/3Few*	*Few*	*Few*	*Many*	**Many+ Few**

The DPMs produced for every vulnerability class of buildings have been related through a vulnerability index which depends on the structural typology and the characteristics of the buildings (number of floors, irregularity etc.).

However, it should be observed that there are some disadvantages related to using empirical methods:

- It is necessary to have many data about post-earthquake damage.
- The seismic risk maps are actually defined in PGA terms while DPM are defined in intensity terms as macro-seismic intensity scale, considering the observed damage of the buildings after the earthquake. Sometimes it is necessary to use correlations between PGA and the intensity that may be hardly reliable.
- When the PGA is used to derivate empirical vulnerability curves, the relation between the frequency of ground motion and the own period of vibration of the structure is not considered.

Vulnerability index methodology GNDT-II (Benedetti & Petrini 1984; GNDT 1993) has been widely used in Italy during the last decades. It is an indirect method because it establishes a relation between seismic action and structural response through a vulnerability index. The method is based on field surveys conducted in order to understand which are the parameters affecting mostly the structural vulnerability, such as plan configuration, type of foundation, structural and non-structural elements, typology and quality of materials etc. There are 11 parameters and for each one of them one of four qualification coefficients K_i (from A=best condition to D=worst condition) is assigned (see Figure 2.11).

The parameters are weighted considering the importance of each of them by using the following Equation (2.2):

$$I_i = \sum_{i=1}^{11} K_i W_i \tag{2.2}$$

#	PARAMETERS	CLASSES $C_{v,i}$				WEIGHT
		A	B	C	D	p_i
1	Type and organization of resisting system	0	5	20	45	1.00
2	Quality of resisting system	0	5	25	45	0.25
3	Conventional strength	0	5	25	45	1.50
4	Building position and foundations	0	5	15	45	0.75
5	Horizontal diaphragms	0	5	25	45	variable
6	Plan configuration	0	5	25	45	0.50
7	In height configuration	0	5	25	45	variable
8	Maximum distance between walls	0	5	25	45	0.25
9	Roof	0	15	25	45	variable
10	Non structural elements	0	0	25	45	0.25
11	General maintenance conditions	0	5	25	45	1.00

Figure 2.11 Classes, score and relative weight of each parameter (GNDT 1993).

Vulnerability index is included into the range 0-382.5 but normally it is normalized within the range 0-100. The minimum value 0 indicates the minimum vulnerability whereas the maximum value 100 the maximum vulnerability. The data derived from past earthquakes are used to calibrate vulnerability functions in relation with vulnerability index I_v and damage factor of buildings having same structural typology and same macro-seismic intensity or PGA, see Figure 2.12.

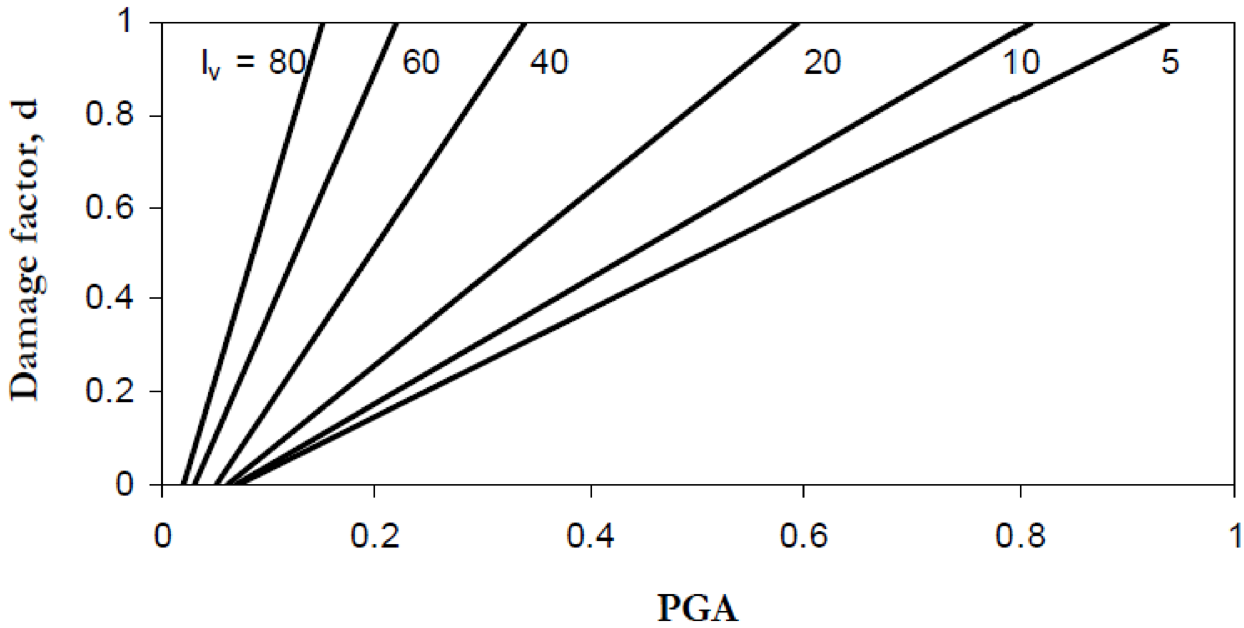


Figure 2. 12 Vulnerability functions in function of damage factor (D) and PGA for different vulnerability indexes (Vicente et al. 2011)

Among the principal projects which used this methodology there are the RISK_UE (An advanced approach to earthquake risk scenarios with application to different European towns, (Mouroux et al. 2004)) financed by the European community and the PROGETTO CATANIA project (GNDT 2000; Faccioli et al. 1999).

Vicente (Vicente et al. 2011) also used a vulnerability index defined similarly to that of GNDT-II but using 14 parameters instead of 11. To obtain the structural damage and the economic damage indicator, a correlation between vulnerability index Iv and vulnerability scale was used as provided by the GNDT-II method (GNDT 1993), in order to use analytical expressions (Bernardini et al. 2007) which correlates seismic risk with damage grade μ_D according to Equations 2.3 and 2.4:

$$\mu_D = \left[2.5 + 3 \cdot tanh\left(\frac{I+6.25 \cdot V-13.1}{Q}\right)\right] \cdot f(V,I) \qquad 0 \leq \mu_D \leq 5 \tag{2.3}$$

$$f(V,I) = \begin{cases} e^{\frac{V}{2}(I-7)} & I \leq 7 \\ 1 & I > 7 \end{cases} \tag{2.4}$$

Where I is the seismic risk (expressed in terms of macro-seismic intensity), V is the vulnerability indicator according to the GNDT-II methods, Q is a ductility factor (assumed equal to 3 for all the typologies of buildings), f (V, I) is a function of the vulnerability and intensity indexes. This last parameter assumes different values in function of the value of I. The mean damage grade μ_D can be also expressed by Equation 2.5:

$$\mu_D = \sum_{k=0}^{5} P_K \cdot D_K \tag{2.5}$$

Where P_k is the probability associated to a specific damage grade D_k, with K [0:5].

After obtaining the mean damage grade for every building, the economic damage indicator was found by using the correlation proposed by FEMA-NIBS (Federal Emergency Management Agency (FEMA) 2003). Equation 2.6 shows a simplified expression that was used:

$$\mu_D = 4 \cdot D_e^{0.45} \tag{2.6}$$

Table 2.4 shows some correlations between economic damage index and damage grade. Economic damage index varies between 0 (no economic damage) and 1 (collapse). As it can be noticed, the values of economic indicators related to a specific damage grade are different for different methodologies used.

Table 2.4 Correlation between damage grade and economic damage index for different methodologies (Vicente et al. 2011).

Damage grade, D_k	0	1	2	3	4	5
Level of damage	No damage	Slight	Moderate	Severe	Very severe	Destruction
Economic damage index, d_e						
ATC-13 (1985)	0.000	0.050	0.200	0.550	0.900	1.000
Bramerini et al. (1995)	0.000	0.010	0.100	0.350	0.750	1.000
HAZUS (1999)	0.000	0.020	0.100	0.500	1.000	1.000
Dolce et al. (2000)	0.000	0.035	0.145	0.305	0.800	1.000

Continuous vulnerability curves, based on damage in a structure after an earthquake were introduced after the DPM. The problem of this method is that the derivation depends on the fact that macro-seismic intensity is not a continuous variable. This problem was surpassed by Spence (Spence et al. 1992) by using Parameterless Scale Of Intensity (PSI) to derivate vulnerability functions based on observed damage using MSK damage scale (see Figure 2.13).

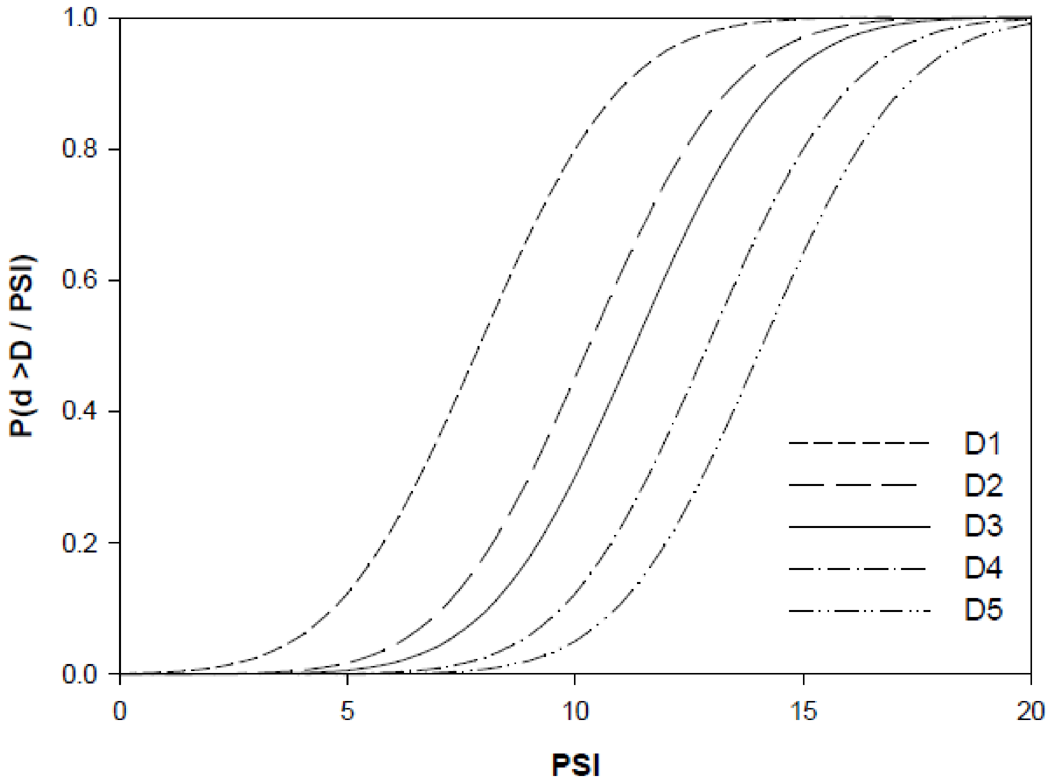


Figure 2.13 Vulnerability curves that use PSI parameter (Spence et al. 1992).

Following studies (Orsini 1999) converted the PSI in PGA using empirical correlation functions. Sabetta (Sabetta et al. 1998) used the data of post-earthquake damage of 5000 buildings to derivate vulnerability curves. They calculated mean damage index as a mean weighted frequency for every damage level. Empirical fragility curves were derived with a binomial distribution. The PGA was derived using the magnitude of events and the distance of the site according to the attenuation relation of Sabetta and Pugliese (Sabetta & Pugliese 1987) hypothesizing a rock soil. Other empirical vulnerability curves which use a normal or lognormal distribution and adopts as a macro-seismic parameter spectral acceleration or spectral displacement were proposed by Rossetto and Elnashai (Rossetto & Elnashai 2003) as shown in Figure 2.14.

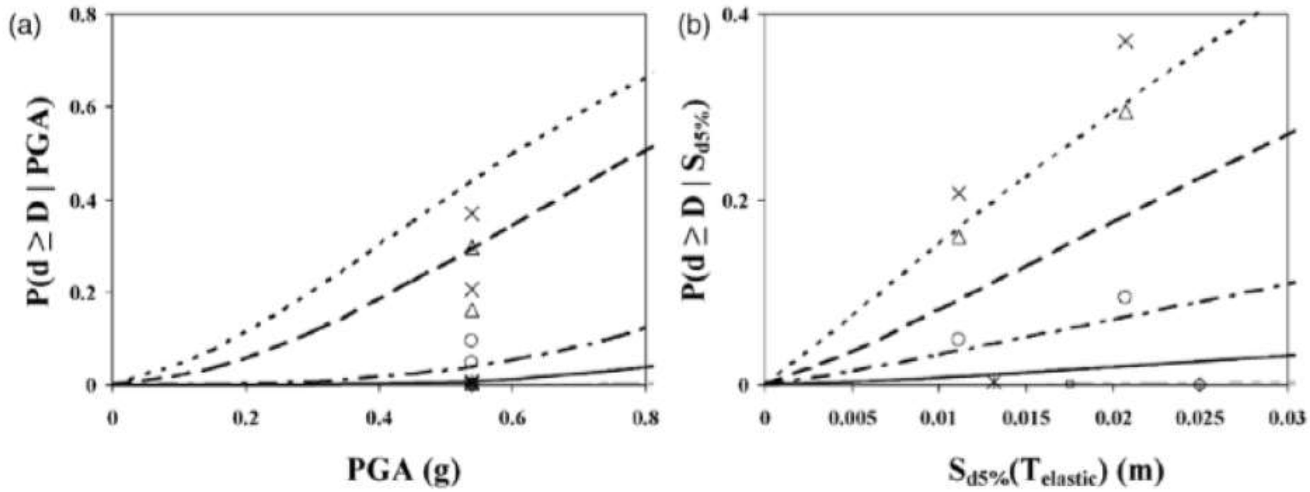


Figure 2.14 Example of the difference in the vulnerability point distribution using observations of low and mid-rise building damage after the 1995 Aegion (Greece) earthquake for different ground motion parameters: (a) PGA and (b) Spectral displacement (Rossetto & Elnashai 2003) (Sabetta & Pugliese 1987)

Another method used is the Screening method. The evaluation of seismic performance of existent reinforced concrete buildings in Japan with less than 6 storeys was developed since 1975 by using the Japanese seismic index method (JBDPA, 1990) (JBDPA 1990). There are available three screening procedures with increased reliable level to estimate the seismic performance of a building, which is represented through a Performance Seismic Index IS, which can be calculated for every floor and every direction using the following equation:

$$I_s = E_0 \cdot S_d \cdot T \qquad (2.\,7)$$

Where E_0 is the original structural performance and S_d is an index related to structural design, T is an index, function of time, which depends on deterioration of the structure.

E_0 is a function of ultimate resistance C and of ductility index F in function of number of storeys and position of the studied floor. S_d is influenced by the irregularity of the stiffness and mass.

The study realized on SAVE Project (Strumenti Aggiornati per la Vulnerabilità sismica del patrimonio Edilizio e dei sistemi urbani) (INGV/GNDT- Gruppo Nazionale Per La Difesa Dai Terremoti 1993) began on 2004 with different Italian universities in collaboration with "Gruppo Nazionale Difesa dei Terremoti". The principal objectives of SAVE project were to implement a database of different structural typologies, developing vulnerability maps to identify the methodologies of vulnerability and damage analyses. In function of the typology of the object studied, the activity was specified for four classes: residential building heritage, public and strategic buildings, monumental heritage and urban system.

The study of the residential building heritage carried on by Zuccaro (Zuccaro 2011) develops a new methodology of vulnerability evaluation which analyses other parameters related to the characteristics of the constructive typologies related to the EMS-98 classification (see Table 2.1). To compare different damage distribution a mean synthetic parameter of damage SPD_V was detected. It should be underlined that the value of SPD represents a measure of the damage, so it provides a simply evaluation in quantitative terms of complete damage of groups of buildings, see Figure 2.15. For every constructive typology a vulnerability class EMS-98 is assigned, see Table 2.5.

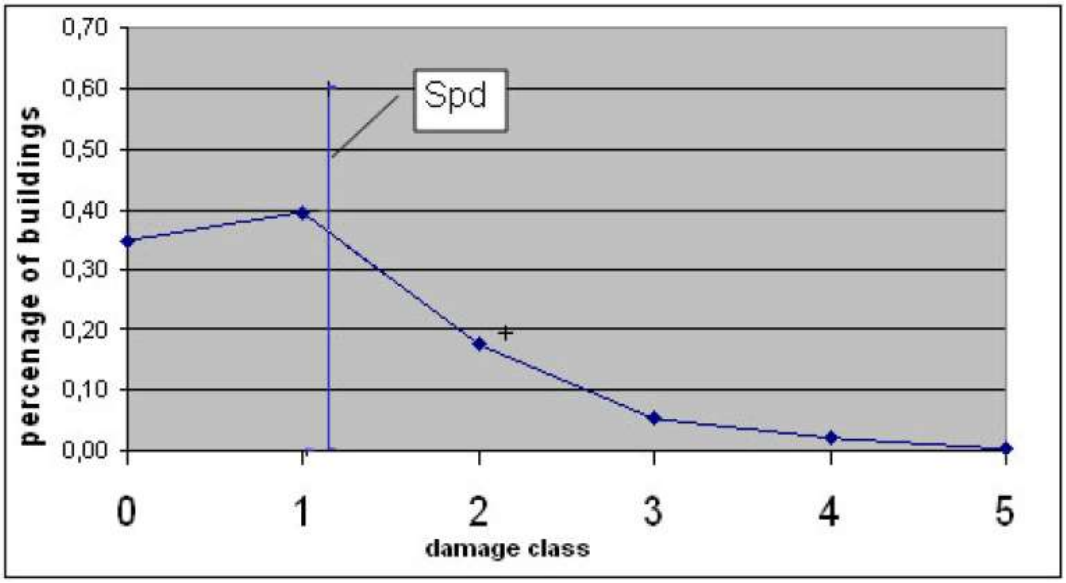


Figure 2.15 Synthetic Parameter of Damage (Zuccaro 2011).

Table 2.5 Building classification according to the typology of vertical structure (Zuccaro 2011).

EMS Classes		Typology of the vertical structure
A		Stones, Irregular Masonry
B		Stones, Regular Masonry
C	C1	Solid Bricks
	Cm	Mixed
D		Reinforced Concrete, Steel

Since it is limited to consider the vulnerability of a building by only the characteristics of vertical loads, other corrective parameters have been detected influencing the behavior of a structure. These can be:

- Typological-structural: horizontal typology structure, roof typology, mixed structure.
- Geometric: number of floors, maximum height, regularity in plan etc.
- Others: year of construction, existing damage.

The contribution of these parameters generates a positive or negative variation of SPD related only to the value of vulnerability class considering only vertical loads. The Figure 2.16 shows how determining the correct value of SPD.

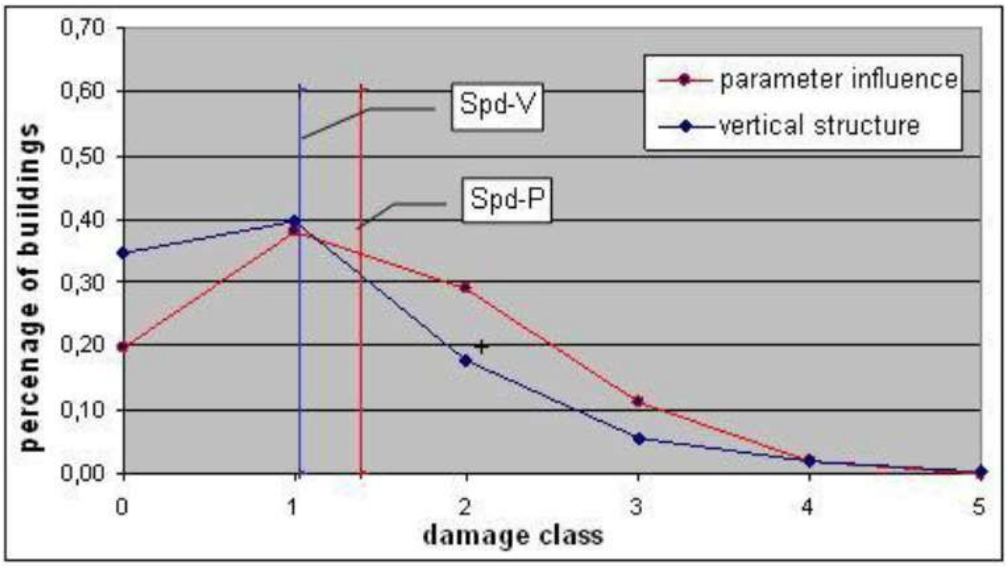


Figure 2.16 Correction of SPD (Zuccaro 2011).

The percentages of variation of SPD for each parameter has been evaluated to correct the original assignment of the vulnerability classes.

The correction procedure of vulnerability can be synthesized as follows:

- For every building, a vulnerability class EMS_V is assigned in function of the structural typology.
- A basic score is assumed as the mean value of SPD_V corresponding to the EMS_V class assigned.
- The basic score is multiplied by an influent coefficient (positive or negative) corresponding to the value of the parameter considered.

- The value calculated with basic score of SPD is summed and the correct score SPD is obtained.
- The vulnerability class is reassigned in function of the correct value of SPD, which derives from a possible shift of vulnerability class according to the one, derived from only vertical structure.

The Equation 2.8 shows how to calculate the corrected PSD is the following:

$$SPD_{EMS} = SPD_{vEMS}(1 + \sum_{s=1}^{n} q_s + \frac{\sum_{j=1}^{m}\sum_{i=1}^{m}\delta_{i,j}(p_j+p_i)c_{i,j}}{m-1} \qquad (2.\ 8)$$

Where q is the value of independent parameter, p is value of dependent parameter, n = number of independent parameters, m is the number of dependent parameters, $c_{i,j}$ is a correlation coefficient, $\delta_{i,j}$ is the Kronecker operator.

At the end, once the correct SPD value is calculated, a vulnerability class is assigned.

2.2.2 Analytical/mechanical methods

The diffusion of attenuation equations in terms of spectral ordinate and the corresponding risk maps led to the development of analytical methods. These methods tend to characterize much more in detail the evaluation of vulnerability in direct terms, which permit a simple calibration of various structural characteristics and risks.

Even though the vulnerability curves and damage probability matrix are derived traditionally using the observed damage dates, recent proposals used computational analyses to exceed some inconveniences of the methods described before. The Figure 2.17 summarize the components that are necessary to derivate analytical vulnerability curves and damage probability matrixes.

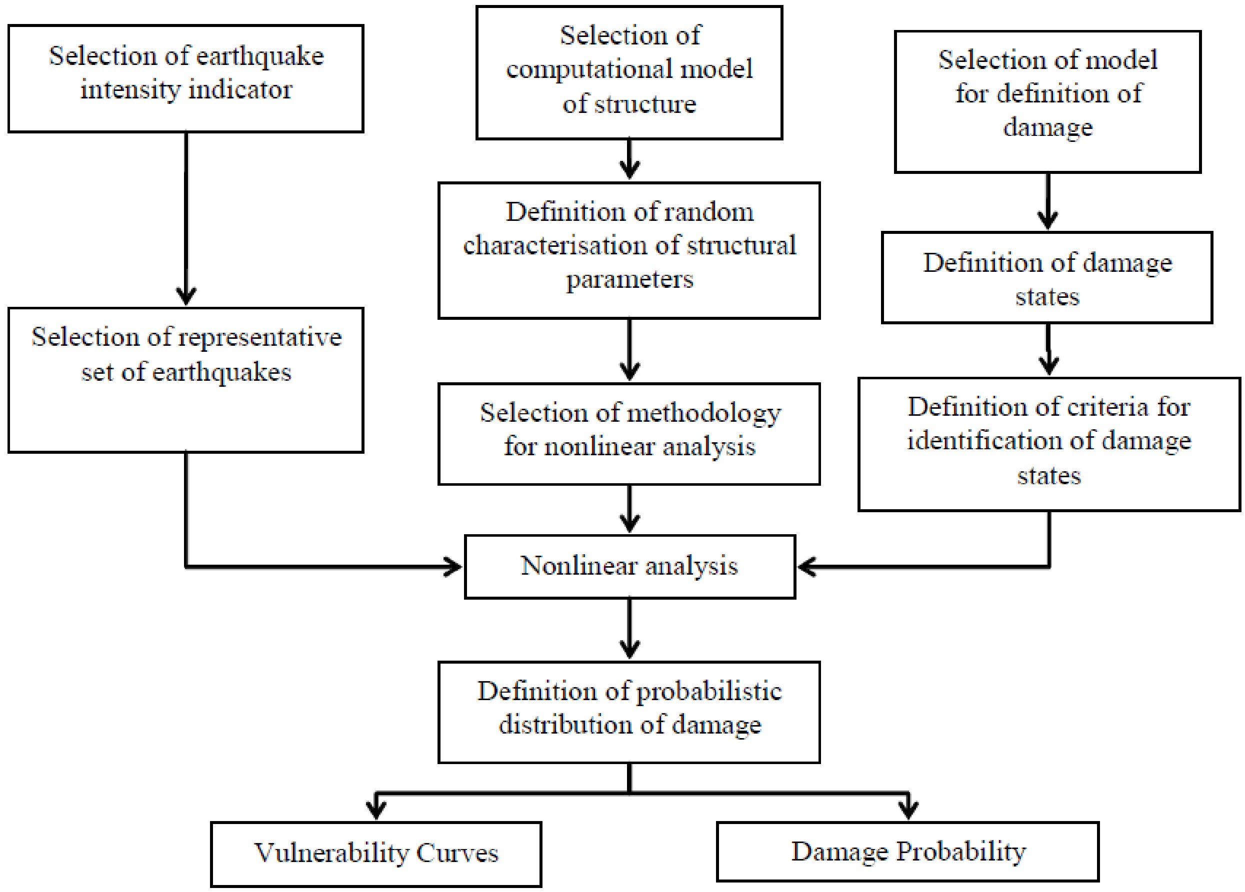


Figure 2.17 Flow diagram which describes the components to calculate analytical vulnerability curves and damage probability matrixes (Calvi et al. 2006).

Singhal e Kiremidjian (1996) (Singhal & Kiremidjian 1996) developed fragility curves and damage probability matrix for three typologies of RC buildings using Monte Carlo simulation. The probability to have structural damage was determined by a non-linear dynamic analysis using the ground motion. To build the DPM, the macro-seismic intensity Mercalli-Modified was used as risk parameter, while the spectral acceleration was used for the generation of fragility curves as shown in Figure 2.18.

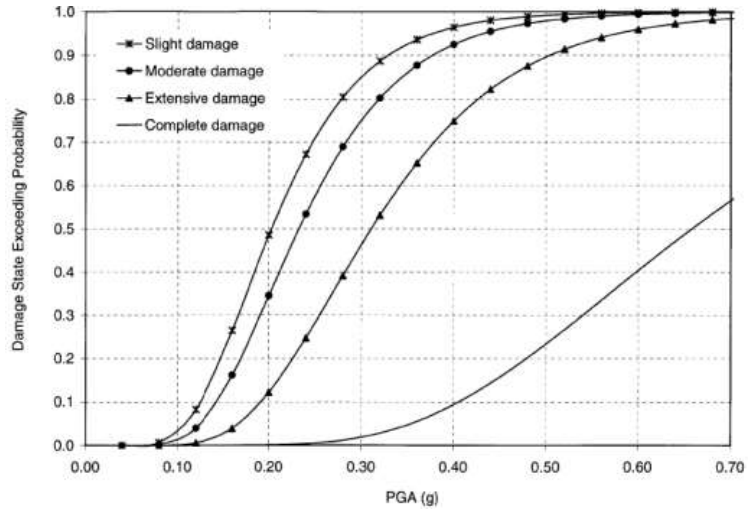


Figure 2.18 Fragility curves (Singhal & Kiremidjian 1996).

One of the principal disadvantages of derivation of analytical vulnerability curves is the elevated computational cost, which needs a big quantity of time to perform the analyses. Furthermore, analytical vulnerability curves cannot be produced easily for different countries or continents with different structural characteristics.

2.2.3 Hybrid methods

The damage probability matrixes and vulnerability curves combines the statistical analyses of damage post-earthquake with the analytic simulation of damage. These models can be advantageous when damage data for different intensity levels are lacking for the geographic areas considered. Furthermore, using observed damage data reduces the computational cost of analytic methods in order to produce vulnerability curves or DPMs. The principal difficulty in using hybrids methods are related to the calibration of analytical results considering that the two vulnerability curves include different uncertain sources and are not directly compared. Many of recent analytic methods use collapse multipliers in order to verify if a certain mechanism causes damage. These methodologies are particularly used for masonry buildings. VULNUS is a method, which has been proposed to evaluate the vulnerability of unreinforced masonry buildings using Fuzzy-Set Theory and collapse multipliers.

The FaMIVE (D'Ayala & Speranza 2002) method is another procedure based on collapse multipliers whose objective is the evaluation of seismic vulnerability of buildings in historical centers. The in-plane and out-of-plane collapse mechanisms are found through the evaluation of the load factor or collapse multiplier using a static equivalent procedure based on limit analysis. A representative number of out-of-plane collapse mechanisms was assumed and for each of them the equivalent capacity has been calculated, being the most vulnerable mechanism that with less capacity, see Figure 2.19.

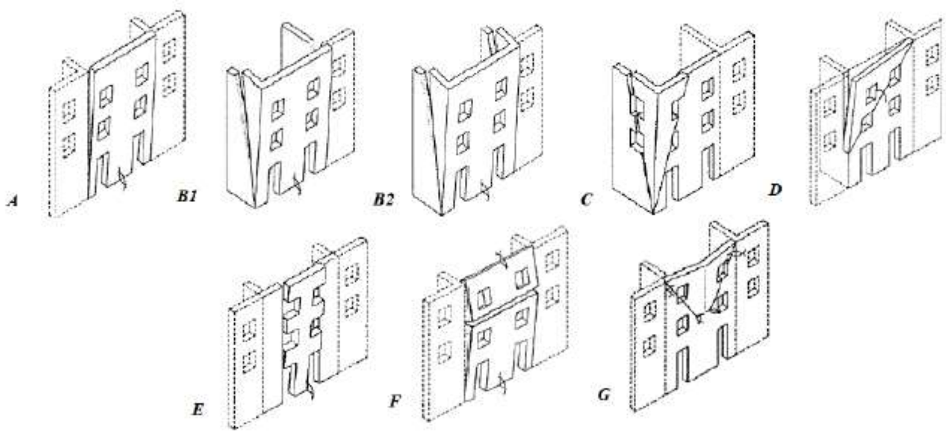


Figure 2.19 Out of plane collapse mechanism (D'Ayala & Speranza 2002).

VULNUS procedure evaluate damage probability but only for limit states that correspond to collapse limit. Therefore, using these procedures in a model aimed at evaluating the losses in terms of different levels of damage can be limited.

HAZUS (HAZard-US) is the result of a project leaded by National Institute of Building Science (NIBS) in collaboration with Federal Emergency Management Agency (FEMA), to develop a methodology applied at national level to estimate the potential losses of an earthquake at urban scale. (Federal Emergency Management Agency (FEMA) 2003; Kircher et al. 2006). The evaluation of damage of buildings are used as an input for other damage modules especially for losses modules, as it is shown in Figure 2.20.

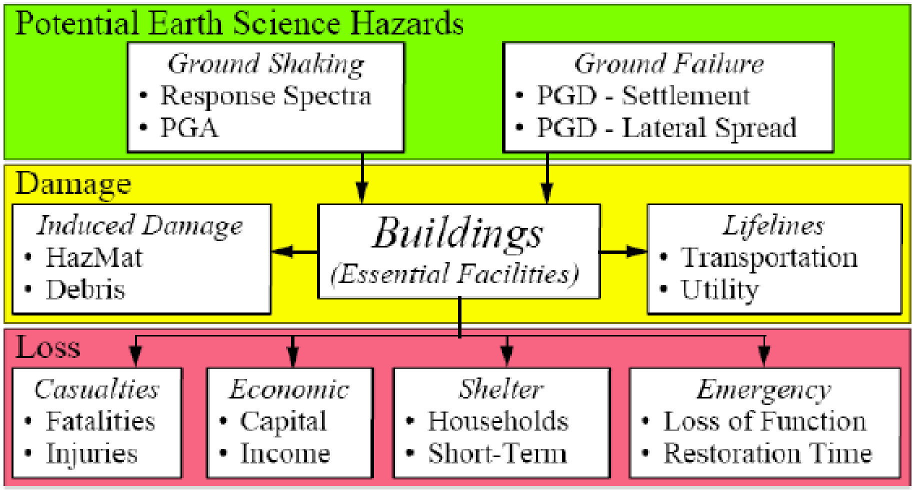


Figure 2.20 Relation between different HAZUS module (FEMA 1999)

The procedure of vulnerability evaluation is based on spectrum capacity method of ATC-40 (ATC 1996). By this way, the performance point of a particular earthquake is found by the intersection between the acceleration-displacement spectrum, which represents the seismic demand generated by the ground motion, and the capacity spectrum (push-over curve) which represents the horizontal displacement of a structure under a lateral increasing load. The capacity spectrum has been developed for each building class, obtaining a medium performance point for every class, which provide the input for vulnerability curves of limit states in order to provide the probability of being at a determinate damage range. A weak point of the methodology is that capacity curves and vulnerability functions, published on HAZUS manual, are derived for representative buildings of the United States and have a limited range of high buildings (see Table 2.6). Therefore, the application of these methods to other countries may encounter some difficulties.

Table 2.6 Model building according HAZUS (FEMA 1999).

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (> 5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4 5	S1L S1M S1H	**Steel Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	**Steel Braced Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
9	S3	**Steel Light Frame**		All	1	15
10 11 12	S4L S4M S4H	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
13 14 15	S5L S5M S5H	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	**Concrete Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	**Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26 27 28	PC2L PC2M PC2H	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
29 30	RM1L RM1M	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
34 35	URML URMM	**Unreinforced Masonry Bearing Walls**	Low-Rise Mid-Rise	1 - 2 3+	1 3	15 35
36	MH	**Mobile Homes**		All	1	10

Giovinazzi & Lagomarsino (Giovinazzi & Lagomarsino 2004) presented a mechanical procedure to evaluate the risk of masonry and RC buildings using spectrum of simplified bilinear capacity which is derived using the equations and the parameters available on seismic design code. However, it should be noted that using the information contained on seismic codes could produce different results, which differ from the real characteristics of building heritage considering that in many countries the buildings do not comply with any design code. Following the HAZUS method, the obtained performance point is inserted into vulnerability curves to obtain the exceeding probability of determined damage level. The mean threshold values of displacement implemented by Giovinazzi (Giovinazzi 2005) are function of ultimate displacement as is shown in Equation 2.9:

$$
\begin{gathered}
S_{d,1} = 0.7d_y \\
S_{d,2} = 1.5d_y \\
S_{d,3} = 0.5(d_y + d_u) \\
S_{d,4} = d_u
\end{gathered}
\tag{2.9}
$$

The first steps on developing the methodology based on displacements were proposed by Calvi (Calvi 1999) which proposed to use the displacements as a fundamental indicator of damage. The procedure used the direct method based on a displacement format where a structure with many degree of freedom (NDOF) is modelled as a singular degree of freedom structure (DOF) using different displacement profiles related to collapse mechanism considering the geometry and property of materials of the building, see Figure 2.21.

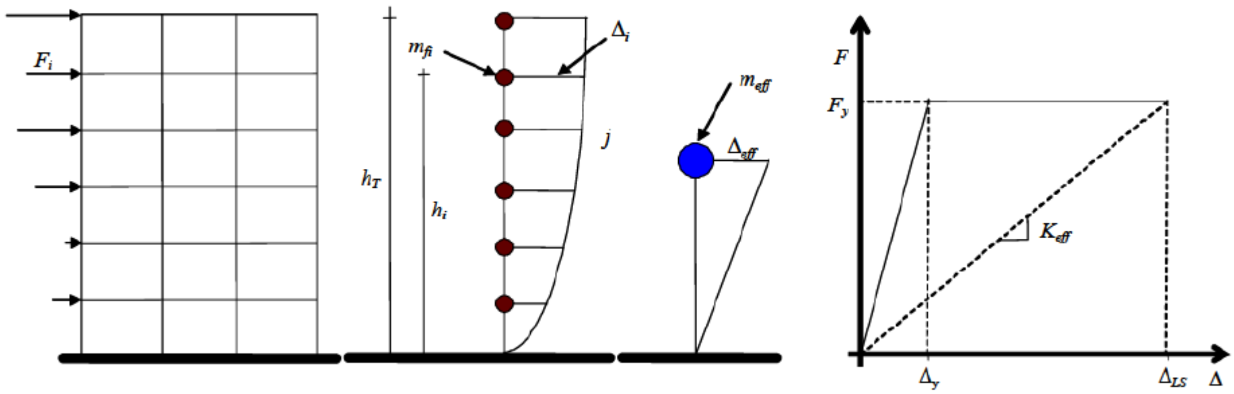


Figure 2.21 Simplified model for a system of DOF (Calvi et al. 2006).

The methodology proposed by Calvi was developed for RC buildings by Pinho (Calvi et al. 2006) named as Displacement-Based Earthquake Loss Assessment (DBELA). In this method, three limit states have been considered.

- LS1-LS2 for structural and no structural damage;
- LS3 for moderated structural damage and extended non-structural damage;
- LS4 for collapse of the buildings.

It should be highlighted that to use these methods a database about seismic activity is necessary, as well as knowledge on attenuation equations and ground conditions, so that to implement a seismic risk evaluation in spectral terms. However, these methods are useful to realize sensible studies to understand how the model used influences the results, the data available and the hypothesis taken in consideration.

2.3 SEISMIC RESILIENCE

2.3.1 Concept of resilience

The resilience concept w developed firstly in the field of ecology. Holling (Holling 1973) defined resilience as a property of a system that measures its ability to absorb changes of different variables and return to an equilibrium state after temporary disturbance. In the last years, resilience became a usual term in the field of risk management. Pelling (Pelling 2003) for instance, affirmed that resilience to natural hazards is the ability of an actor to cope with or to adapt to hazard stress. It is a product of the degree of planned preparation undertaken in the light of potential hazard, and spontaneous or premeditated adjustments made in response to felt hazard, including relief and reuse. Concept of seismic resilience considers also the social dimension. According to (Bruneau et al. 2006), community seismic resilience is defined as the ability of social units to mitigate hazards, to contain the effects of disasters when they occur. Also it is defined as the ability to carry their recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes.

The International Strategy for Disaster Reduction, Hyogo Framework for Action 2005-2015, called “Building the resilience of nations and communities to disasters” gives a definition about the resilience. Resilience is determined as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure, and is determined by the degree to which the social system is capable of organizing itself to increase its capacity of learning from past disasters for better future protection and to improve risk reduction measures (Fera 1997).

It can be achieved both working on structural aspects and emergency response and strategies, involving institutions and organizations, and in particular those related to essential functions for community well-being, as acute-care hospitals.

2.3.2 Resilient City

Therefore, the most important aspect concerns how to define and apply the strategies in order to provide the required resiliency to the city.

In order to answer to the question, it is necessary to observe the city and to understand how it works. A city should be considered as a network system, characterized by a main trunk and some secondary branches, whose elements are hierarchically less important than the primary ones. In terms of response to an earthquake, therefore, trunk elements must have a faster response, because they are charged of main activities of city. Adopting this approach, it is required to define what elements of a city can represent the minimum set able to guarantee functionality.

2.3.3 How to Identify a Resilient City?

The main phases of a disaster management are shown in Figure 2.22.

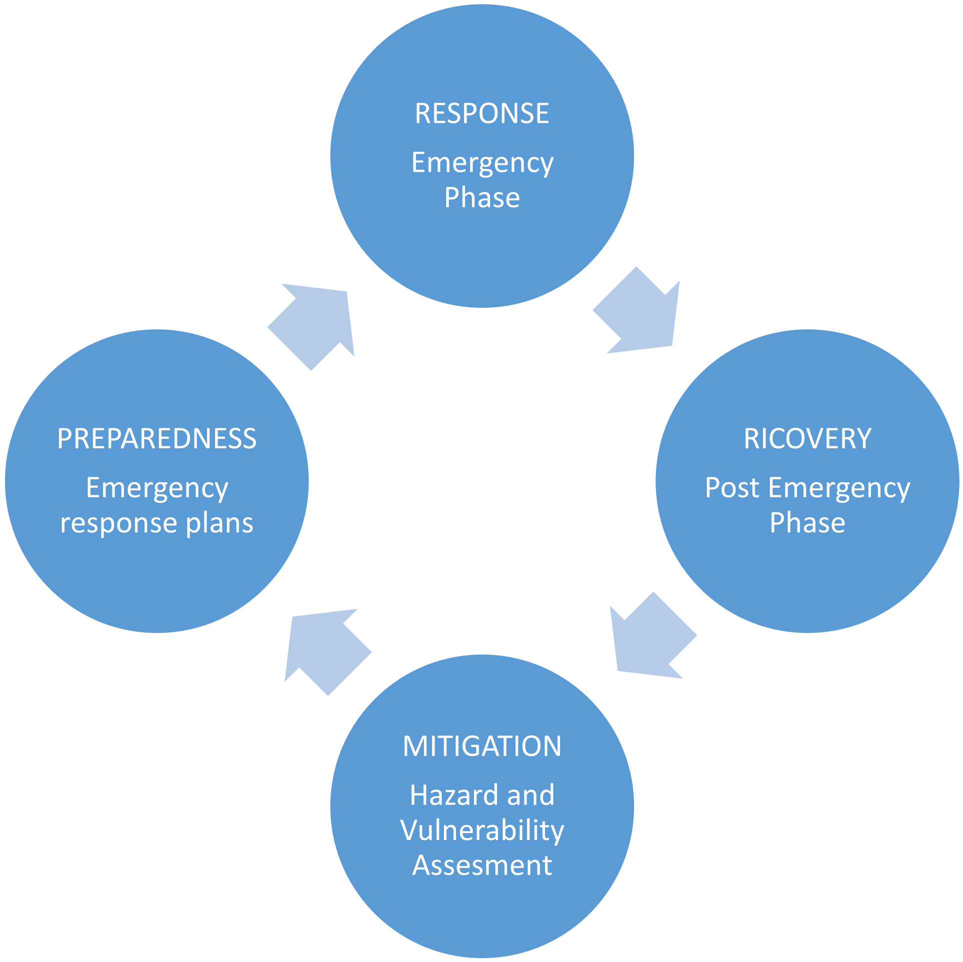


Figure 2.22 Four phases referred to a disaster management.

According to these phases, it is possible to determine the minimum sets of elements composing a resilient city. In peacetime, in the Mitigation phase it is possible to define an expected seismic scenario. After during preparedness phase, once the expected seismic scenario is defined, the identification of the following elements is needed:

- requesting prevention, which do not satisfy acceptable vulnerability levels;
- emergency phases, referred to the expected seismic scenario;

- overpass the emergency phase, referred to the expected seismic scenario, and to re-establish normality.

Prevention phase will be characterized by all the actions aiming to bring elements composing sub-sets in acceptable vulnerability conditions.

In Figure 2.23 main systems of resilient city are shown, and their main components are synthetically listed. Their identification depends on functional, morphological and dimensional characteristics of the considered urban system (Olivieri 2004).

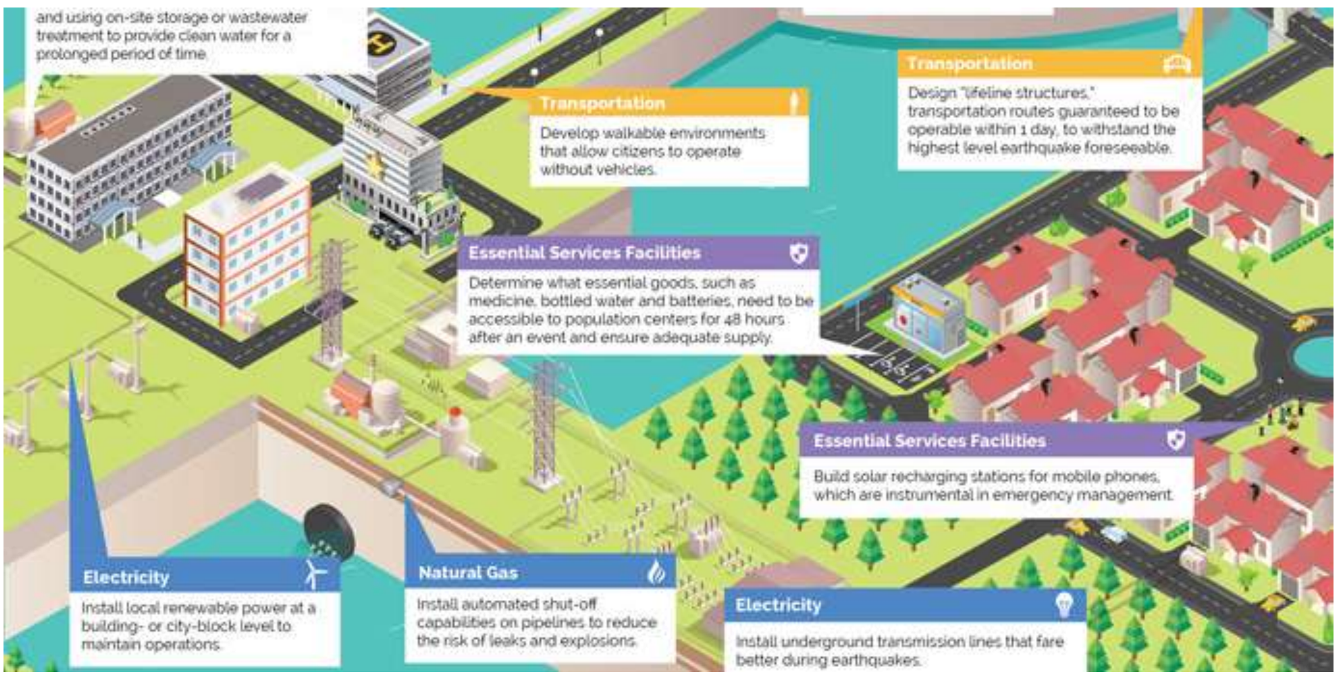


Figure 2.23 Systems composing resilient city [Jake Herson].

- Main Lifelines Systems: all these activities assume that main services work (water, gas, electricity distribution and communication must be efficient).
- Accessibility system: in order to guarantee a minimum of normal cities functionalities. It consist in first, identification of main roads, useful as way of escape and allowing access

to strategic buildings, as hospitals, and to shelter areas, then, roads connecting quarters and finally internal roads.

- Open and Safe areas Systems: at the same time, open spaces where gathering people, offering a recover, disposing a field hospital and so on, must have been identified, with strong guarantee of their safety.
- Strategic Building Systems: emergency activities need some buildings where decisions can be made, but firstly need hospitals, military buildings, in order to help hit people.

2.4 POLICIES OF VULNERABILITY REDUCTION AT URBAN SCALE

The concept of vulnerability at urban scale as a sum of the vulnerabilities of the single components is not considered anymore in planning policies of mitigation of risk. The new trend consists in considering the interdependency of buildings as an overall configuration set, see Figure 2.24. A definition of vulnerability at urban scale is the "*tendency of a settlement considered as a whole to undergo physical damage and loss of organization and functionality during an earthquake*" (Fazzio et al. 2010).

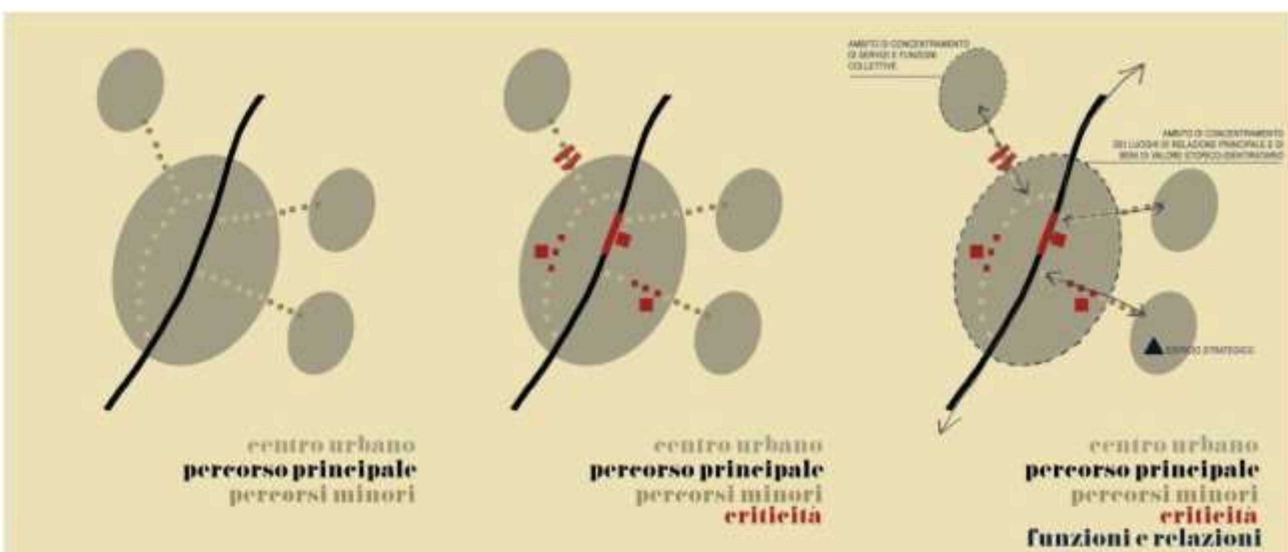


Figure 2.24 Functional view of a settlement (Fabietti V 1999).

The urbanism considers also social-economic relation. The urban system should be considered as a functional system, a living organism able to provide all the vital functions. Urban functions are all those characteristics which define an urban system and transform a physical area into a city. A functional model of a city can be compared with a mechanical model where the structural parameters of ductility, resistance and stiffness are replaced by different levels of urban standards. According to this view, a damage is considered as a loss of performance level. The aim of advanced planning then becomes to limit as much as possible this kind of loss, so that the system can return to its normal standard condition in the shortest period, as shown in Figure 2.25.

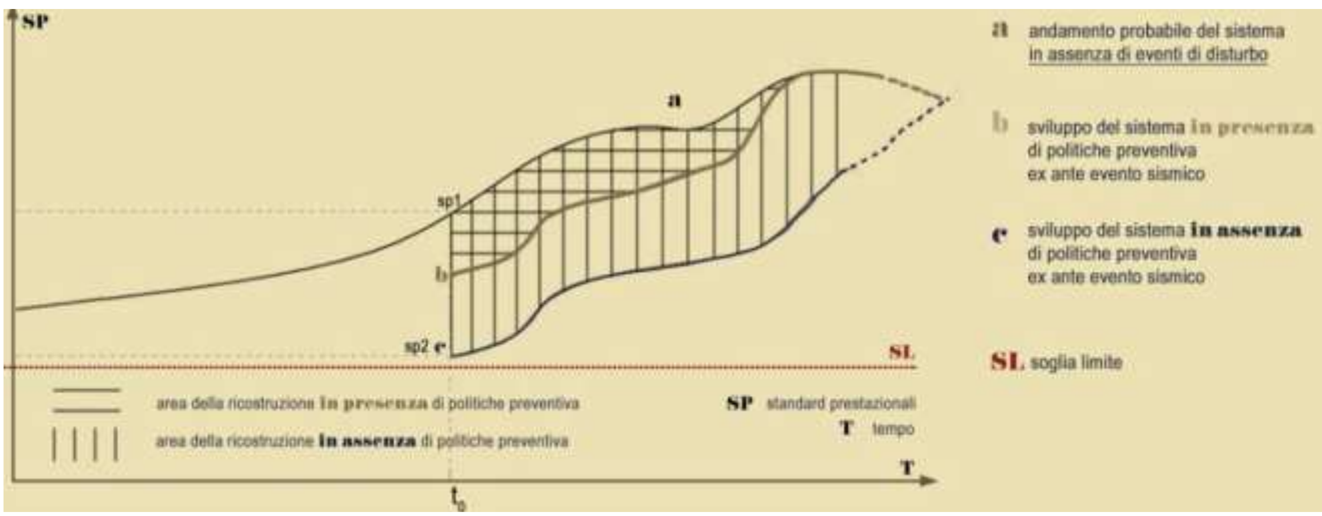


Figure 2.25 Effects of advance planning on post-seismic functionality (Fabietti V 1999).

The curve “a” in Figure 2.25 represents the probable trend in case of absence of disturbing events. The curve “b” represents the development of the system in the case of application of prevention policies and curve “c” represents the development of the system if there are no prevention policies.

If t_0 is the exact moment a seismic event hits the city and s_{p1} is its original standard level, the performance loss s_{p1}-s_{p2} without advanced prevention planning is significantly bigger than that undergone having applied before these urban policies. It is also acknowledged the existence of a threshold, or a minimum performance level below which it becomes impossible for the settlement to recover and, in analogy with the collapse of a structure, the city experiences a complete abandonment.

2.4.1 Minimum urban structure: definition, contents and objectives

The ideal aim of advance-planning policies would be not to have any performance loss after an earthquake. However, especially in historical city centers, this would be extremely expensive and would require a very long period to accomplish all the strengthening works needed.

If on one hand a certain amount of damage, defined as acceptable risk level, has to be admitted, on the other hand it becomes important to assess which is the maximum performance loss that a city can experience without being abandoned. In other words, considering the settlement as a mechanical system, the essential elements' configuration has to be founded.

It is impossible, in terms of cost and time to guarantee the protection of the whole entirety. The minimum urban system is that essential system able to assure the protection of priority elements defined vitals, accepting the loss of parts, which have secondary importance in a system (acceptable risk level). The minimum urban system consists in the individuation of the "city into the city" where all the urban functions, necessary to continue the life in the urban center, are concentrated.

The minimum urban structure (Fabietti V 1999) is defined as the combination of:

- Routes (from and to the city, roads, waterways or railways);

- Open spaces (parks, parking spaces, squares);

- Urban functions (trade, education, workplaces, etc.);

- Strategic buildings (hospitals, fire brigades, city hall, etc.).

All the aforementioned elements allow the city not only to deal with the first emergency phase immediately after the earthquake, but also guarantee the maintenance and recover of all ordinary urban, social-economic and connective activities that are necessary, in the second phase, to prevent the city from being abandoned. The adjective “minimum” highlights the importance of carefully choosing only the elements whose collapse or even interruption of use would compromise the behavior of the entire system.

2.4.2 Limit conditions for settlements

In Italy with the approval of the new standards for construction (Nuove Norme Tecniche per le Costruzioni, 2008), a performance-based approach for buildings’ design has been introduced, with the definition of four “limit states”:

- Operativeness (SLO);

- Damage (SLD);

- Life-saving (SLV);

- Collapse (SLC).

They can be described as thresholds or physical and functional damaging levels, expressed both qualitatively and quantitatively. Four performance levels of buildings are determined for increasing vulnerability. They point out the severity of damage undergone after an earthquake, and the eventual amount of time needed to restore the full functionality or allow the habitability. In particular, they are:

- Fully operative;

- Operative;

- Life-saving;

- Near collapse.

Passing to the urban scale, four limit conditions can be described likewise for a settlement, where building's damaging levels are replaced by performance loss levels of the urban system (Staniscia 2013), see Figure 2.26.

Limit states for buildings (NTC 2008, § 3.2.1)	Limit states for settlements (Olivieri et al., 2013)
SLO **Limit state of operativeness**	**CLO** **Limit condition of settlement operativeness**
After the earthquake, the construction as a whole, including structural and non structural elements, as well as all the facilities consistent for its function, does not have to undergo any damage or significant interruption of use.	After the earthquake, the urban settlement as a whole does not undergo any damage or significant interruption of use. In particular are guaranteed the pre-seismic persistence and efficiency of public and private functions, connection routes and technological networks, and the preservation of residential activity.
SLD **Limit state of damage**	**CLD** **Limit condition of settlement damage**
After the earthquake, the construction as a whole, including structural and non structural elements, as well as all the facilities consistent for its function, suffers damages not leading though to put occupants at-risk and not significantly compromising the building's resistance and stiffness towards vertical and horizontal loads, keeping it immediately usable even if with a partial interruption of use in some parts of the facilities.	After the earthquake the urban settlement as a whole undergoes physical and functional damages that will not lead to a significant compromise the continued use of strategic urban functions, ordinary activities, included residential ones, connections to and from the urban centre and the territorial context, although with a partial interruption of use (temporally or spatially, on limited extensions), or rather a lowering of performance levels.

SLV **Limit state of life-saving**	**CLV** **Limit condition of settlement life-saving**
After the earthquake, the construction undergoes breakages or collapses of non structural and system elements or significant damages to structural parts to which is linked a serious loss of stiffness towards horizontal loads; the building keeps on the other hand some of its resistance and stiffness towards vertical loads and a safety factor against seismic collapse	After the earthquake the urban settlement as a whole undergoes physical and functional damages that lead to the interruption of use of some of existing urban functions in the all area or most of it. The urban settlement keeps its functionality of all strategic function for the emergency response and the post-seismic recover whether inside or outside of it, directly related and dependent, and their connection and accessibility within the territorial context. It is guaranteed the possibility of keeping and resuming the pre-existent residential function according to spatially and temporally extensions consistent with the preservation and recover of the settlement essential features (determined regarding the specific aspects of every city) even after a limited or consistent interruption of use.

SLC **Limit state of collapse**	**CLC** **Limit condition of settlement collapse**
After the earthquake, the construction undergoes severe breakages and collapses of non structural and system elements and very serious damages to structural parts; the building however keeps a safety factor towards vertical loads and a scarce one also against collapse due to horizontal loads.	After the earthquake the urban settlement as a whole undergoes physical and functional damages that lead to the interruption of use of many existing urban functions, including residential one. The urban centre however keeps functionality of most strategic function for the emergency response and the overall system of those needed for the recover, located internally or externally directly related and dependent, and their connection and accessibility within the territorial context

Figure 2.26 Comparison between limit states/conditions for buildings/settlements (Staniscia 2013).

2.5 EVALUATION OF EMERGENCY LIMIT CONDITION

After a seismic event, it is verified at the same time physics and functional damage, which can conduct to the interruption of almost totality of the present urban functions. The Emergency Limit Condition (ELC) (Commissione tecnica per la microzonazione sismica, 2013) of an urban area is defined as that condition where the urban area conserves the efficiency of most part of strategic functions for the emergency, the accessibility and the connections on the territorial contest.

The analysis of the ELC of the urban area is applied using the set of forms from Technical Commission at article 5 of O.P.C.M. 3907/2010.

This analysis implicates:

a) Individuation of buildings and areas which guarantee strategic function of emergency.

b) Individuation of accessibility of infrastructure and connections at a territorial context of the buildings and areas defined at point a) and eventually critical elements.

c) Individuation of structural aggregates and single structural units, which can interfere with the accessibility infrastructure and connection with territorial connections.

Five data sheets compose the set form and they are:

- Strategic building (ES)
- Emergency area (AE)
- Accessibility Infrastructure/Connection (AC)
- Structural aggregate (AS)
- Structural unity (US)

The procedure for the analyses of the ELC can be summarized as follows:

- The buildings destined to strategic functions considered essential are individuated on the Regional technical maps;
- A sequential identification is attributed to each strategic function;
- The possible structural aggregates which belong to strategic buildings are individuated;
- The emergency areas are individuated;

- The connection routes between strategic buildings and emergency areas are individuated;
- The infrastructure routes which guarantee the accessibility to all the elements are individuated;
- The aggregates or single isolated buildings, interfering with the infrastructure routes or with the emergency areas, are those with height H bigger than the width of the route or the limited area.
- The identification of every element detected before is defined on a map.

The objective is the individuation of measures for the mitigation of seismic risk at urban scale, aimed at the protection of buildings, as well as of the economic properties and vital elements of the community.

The key element is the conceptual and operative definition of ‘Minimum urban structure’, which considers both the mitigation of seismic risk and the urban planning.

The minimum urban structure represents in fact that part of the urban system, which is indispensable to be conserved efficiently after an earthquake in order to guarantee a fast recovery of the normal condition. The simple reason is that the minimum urban structure represents the ‘heart area’ of the city and provides the base to reconstruct the actual prospective of the urban development, see Figure 2.27.

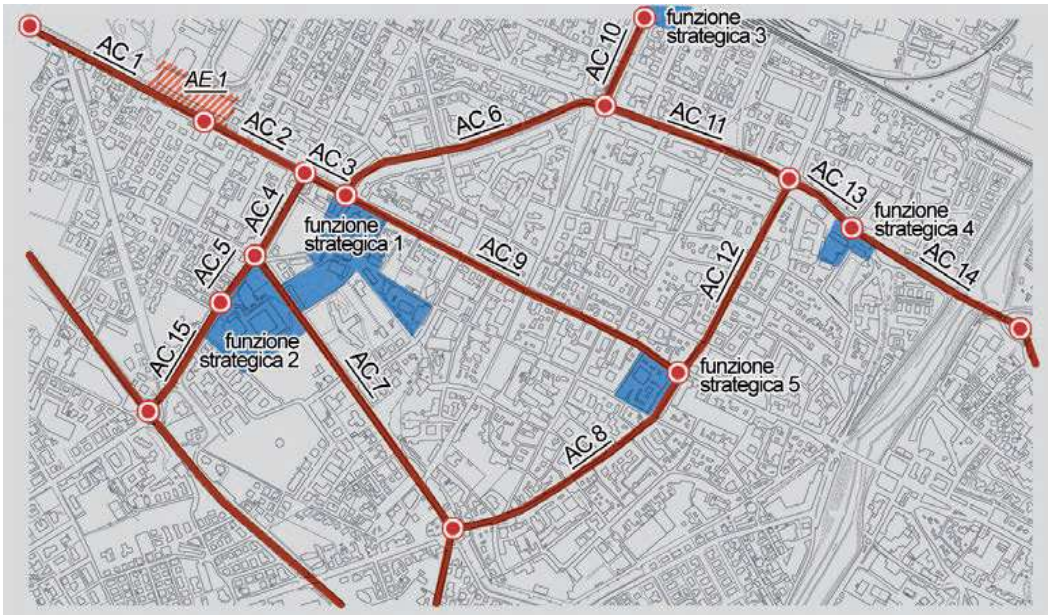


Figure 2.27 Individuation of every element on a map (Protezione Civile guidelines).

2.6 CASE STUDIES OF THE ASSESSMENT OF THE SEISMIC RISK OF URBAN CENTRES

Several researches have established relations in the above mentioned methodologies and the seismic inputs with the purpose to obtain the seismic risk estimation of the urban centres. The different studies have considered different approaches and have been applied for different levels. In the following section, three researches are presented concerning three different cases-studies: the city of Barcelona (Spain), Coimbra (Portugal) and Concordia della Secchia (Italy).

2.6.1 Application to Barcelona using RISK-UE method

The European Risk UE project proposed an advanced approach to earthquake risk scenarios. It was driven by (Mouroux et al. 2004) as a plausible assessment of the direct and indirect damage. The procedure proposed by Risk-UE project is approximation and guideline to perform a holistic assessment and evaluation of the seismic risk in urban centers.

The case-study of the city of Barcelona was carried out by Lantada (Lantada 2007) in the framework of RISK-UE. In this research, she proposed a seismic risk assessment using advanced methodologies and GIS techniques, applying the vulnerability index method (Iv) based in the available data of the Municipal Informatics Institute (MII) through the service of Civil protection of Barcelona Government, and the procedure established by EMS-98. The second methodology applied was the Capacity Spectrum Method (CSM) that considered four non-null damage states and defined the seismic action in terms of response spectra and the building capacity by means of its capacity spectrum (Lantada 2007). The outputs of the seismic risk evaluation drew up risk maps thanks to the use of GIS information. The results were coherent with the historical evolution of the evaluated city and its current state, as well as with the characteristics of the soils. In general terms, a radial structure of expected damage was found, showing a greater damage in *Ciutat Vella*, as shown in the Figure 2.28.

It is important to highlight that the evaluation of the buildings vulnerability in the research of Lantada (Lantada 2007) is first level I, subdividing the building by general category. Therefore, this approach did not consider the actual structural behavior of each different structure.

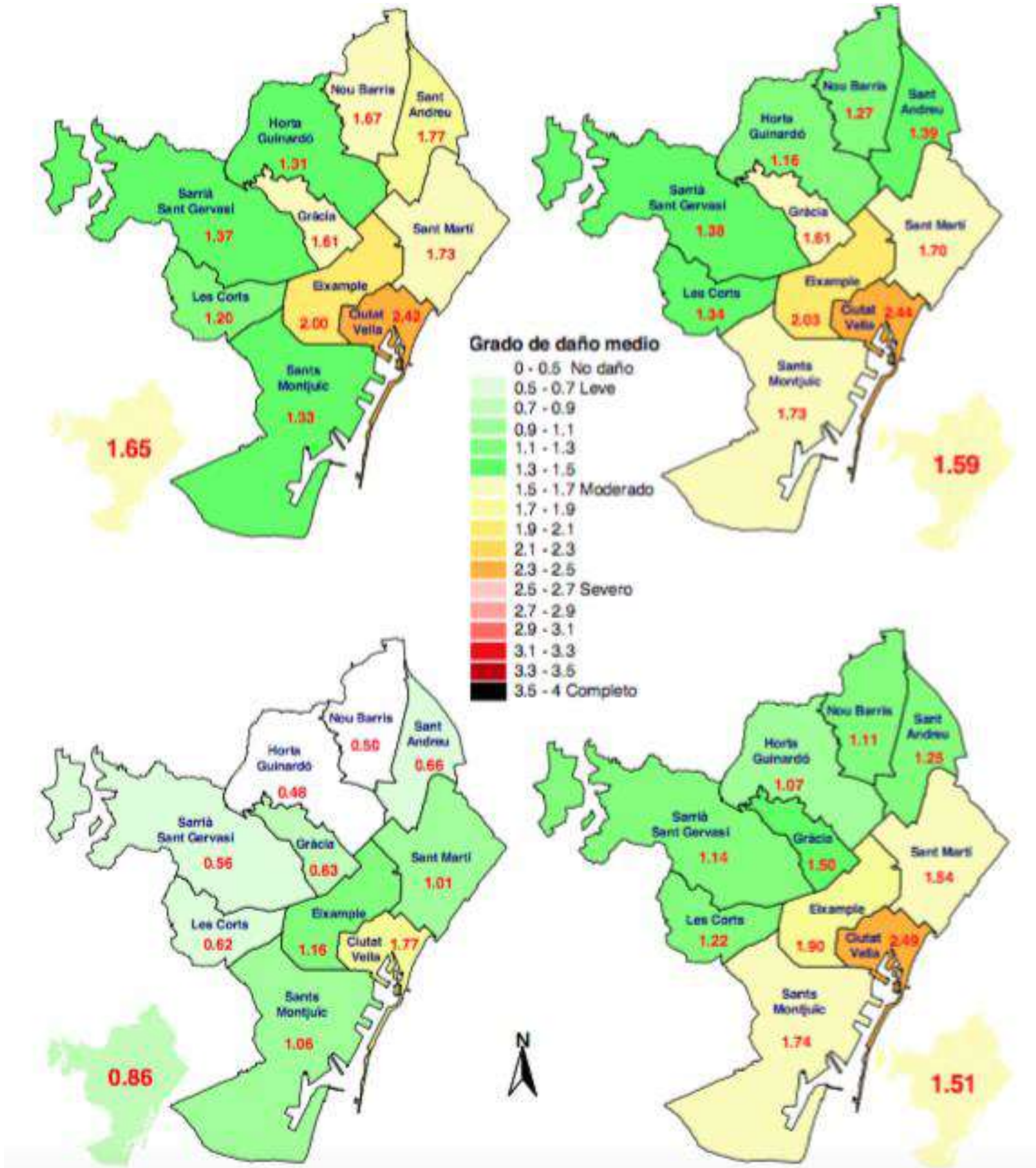


Figure 2. 28 Damage grade for two methods (vulnerability index method above and capacity spectrum method below). Deterministic scenario (Left) and Probabilistic scenario (Right). (Lantada et al. 2009).

2.6.2 Application to the old city center of Coimbra, Portugal

Another example of seismic risk estimation model is the proposed by Vicente et al. (2008) which evaluated the seismic risk of built-up areas associated to the level of earthquake hazard, building vulnerability and level of exposure. In general, the proposed methodology can be considered a combined method, and suggests the calculation of the vulnerability index of buildings, to then evaluate physical damage related to seismic intensity. The main research target was to obtain damage and loss scenarios for the city centre of Coimbra, Portugal, in order to identify building fragilities and reduce the seismic risk. (Vicente et al. 2008). The proposed methodology is similar to the GNDT II level approach (GNDT, 1994) with some modifications. The vulnerability index is calculated as a weighed sum of 14 parameters, instead of the original 11 according to GNDT II, see Table 2.7.

Table 2.7 Proposed vulnerability index I_v, parameters and associated scores (Vicente et al. 2011).

PARÂMETRO		Classe C_{vi}				Peso
		A	B	C	D	p_i
P1	Tipo e organização do sistema resistente	0	5	20	50	0.75
P2	Qualidade do sistema resistente	0	5	20	50	1.00
P3	Resistência convencional	0	5	20	50	1.50
P4	Distância máxima entre paredes	0	5	20	50	0.50
P5	Altura do edifício	0	5	20	50	1.50
P6	Posição do edifício e fundações	0	5	20	50	0.75
P7	Localização e interacção	0	5	20	50	1.50
P8	Irregularidade em planta	0	5	20	50	0.75
P9	Irregularidade em altura	0	5	20	50	0.75
P10	Desalinhamento de aberturas	0	5	20	50	0.50
P11	Diafragmas horizontais	0	5	20	50	1.00
P12	Tipo de cobertura	0	5	20	50	1.00
P13	Danos estruturais identificados	0	5	20	50	1.00
P14	Elementos não-estruturais	0	0	20	50	0.50

ÍNDICE DE VULNERABILIDADE

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i$$

$$0 \leq I_v^* \leq 650$$

(Índice normalizado, $0 \leq I_v \leq 100$)

The methodology of Vicente et al (2003) was applied to the majority of buildings of the old city centre of Coimbra. Not all the information was available for every building. He proposed a simpler approach in function of the mean values attained from the detailed analysis, taking into account that the masonry building characteristics are homogeneous in this area. The mean value of the vulnerability index obtained for all masonry buildings from the first detailed evaluation was used as a typological vulnerability index (average value) that can be affected by modifiers of the mean vulnerability index for each building. The classification of the modifier factors can reduce or aggravate the final vulnerability index as the sum of the scores for all the modifiers. The modifiers are exactly some of the parameters of the vulnerability index definition as shown in Table 2.8. Figure 2.29 shows a plot result from the GIS tool, and in particular an estimation of building collapse and global results for different vulnerability values.

Table 2.8 Vulnerability parameters and scores (Vicente et al. 2011).

	Classe de Vulnerabilidade, C_{vi}			
	0	5	20	50
Factores modificadores do índice de vulnerabilidade	**A**	**B**	**C**	**D**
P5 - Número de pisos	-4.62	-3.46	0.00	6.92
P6 - Posição do edifício e fundações	-0.58	0.00	1.73	5.19
P7 - Localização e interacção	-1.15	0.00	3.46	10.38
P8 - Irregularidade em planta	-2.31	-1.73	0.00	3.46
P9 - Irregularidade em altura	-2.31	-1.73	0.00	3.46
P12 - Tipo de cobertura	-3.08	-2.31	0.00	4.62
P13 - Danos estruturais identificados	-3.08	-2.31	0.00	4.62
Amplitude máxima de modificação, ΣI_v	-17.12	-11.54	5.19	38.65

Pontuação do factor modificador:

$$\frac{p_i}{\sum_{i=1}^{7} p_i} \times (C_{vi} - \overline{C}_{vi})$$

p_i: peso do parâmetro, i, no cálculo de I_v

$\sum_{i=1}^{7} p_i$: somatório dos pesos de todos os parâmetros

C_{vi} : classe do parâmetro modificador

$\overline{C}_{vi}$: classe de vulnerabilidade média do parâmetro, i (*)

* - definido pelos valores da análise detalhada (410 edifícios)

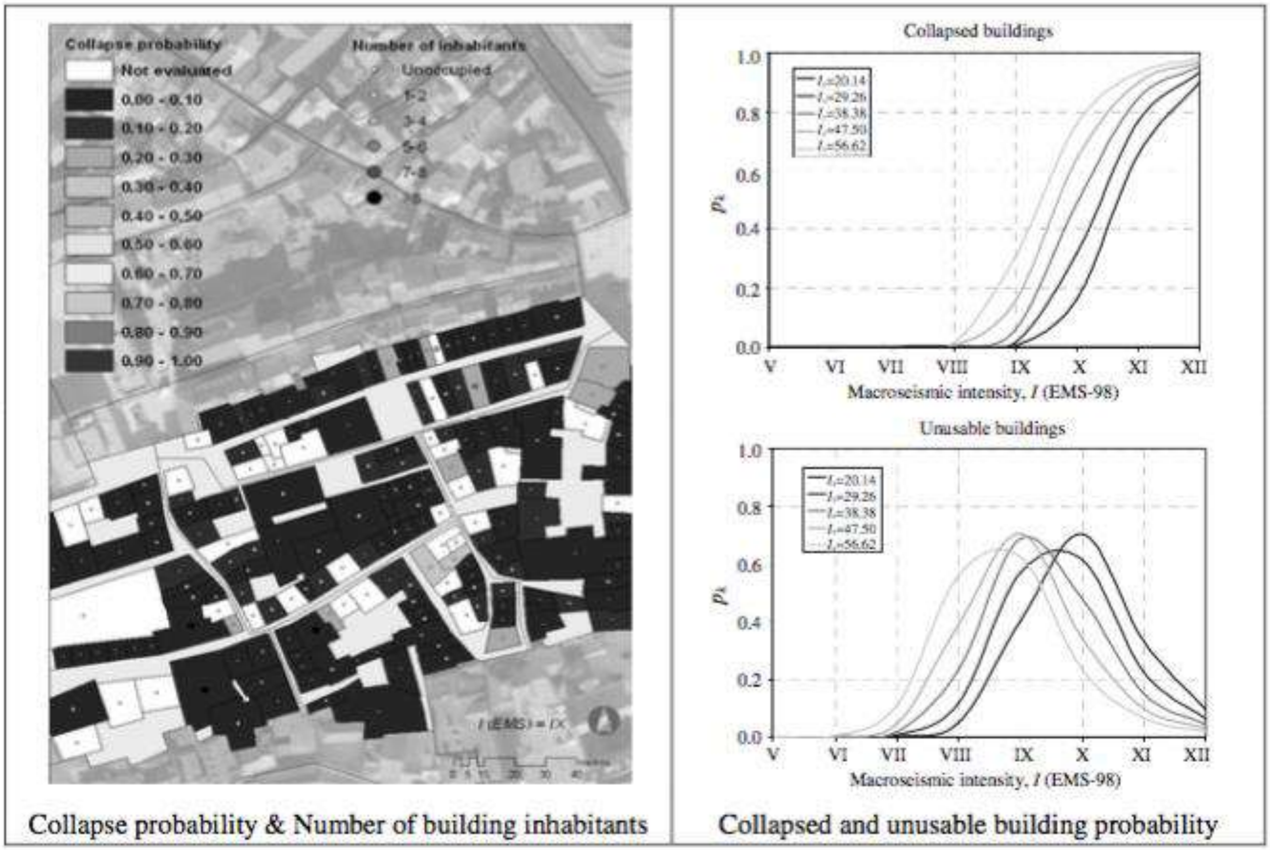


Figure 2.29 Mapping layer results and global result (Vicente et al. 2011).

2.6.3 Application to Sessa Aurunca, Italy

Formisano (Formisano et al. 2011) studied this aspect considering a five units aggregate of historical city nucleus of Sessa Aurunca, in the Italian province of Caserta (see Figure 2.30).

Figure 2.30 Aggregate effect: a) floor plan; b) building no. 1; c) building no. 2; d) building no. 3; e) building no. 4; f) building no. 5 (Formisano et al. 2011).

He proposed an integration of the original GNDT-II form (that now is considered valid only for detached buildings) with other 5 parameters to describe the positive/negative effects of being in an aggregate. Vulnerability indexes indeed can increase but also decrease, as close by constructions can sometimes work as a “restraint”, mitigating in this way the earthquake effects. Scores and weights have been attributed to these parameters by implementing a FEM model with the software 3MURI by S.T.A.DATA (see Figure 2.31) and are shown in Table 2.9.

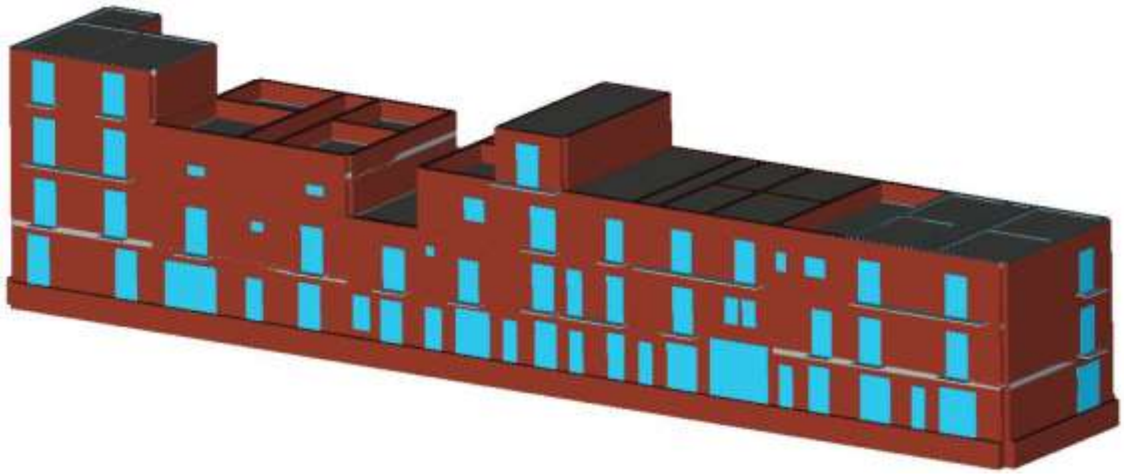


Figure 2.31 FEM model of the masonry aggregate studied by (Formisano et al. 2011).

Table 2.9 Additional parameters to the GNDT-II forms by Formisano (Formisano et al. 2011) for masonry buildings in aggregate.

#	PARAMETERS	CLASSES $C_{v,i}$				WEIGHT
		A	B	C	D	p_i
1	Interactions in elevation	-20	0	15	45	1.00
2	Floor plans interactions	-45	-25	-15	0	1.50
3	Presence of offset ceilings	0	15	25	45	0.50
4	Structural of typological heterogeneity	-15	-10	0	45	1.20
5	Percentage difference within facade openings	-20	0	25	45	1.00

Formisano stated that only a few number of constructions were studied, so while results were considered promising, they need to be validated through numerical and theoretical studies on a larger number of building aggregates. Examining the aggregates parameters of the Formisano method it is noticed that the five parameters added to the eleven original form gives an excessive variation and this should be in a range of 30%. After integrating the new parameters to the study taken in exam, it is noticed that the vulnerability index decreases considerably.

2.6.4 Application to Concordia della Secchia, Italy

Basaglia (Basaglia 2015) carried out recent studies by working on a model of seismic risk assessment based on the method used by Vicente et al. (2008) and complemented with innovative approaches. The proposed methodology was applied on the historical centre of Concordia Sulla Secchia, Modena, Italy. The city underwent severe damages by the last earthquake of 29th May 2012. After this important event, a data survey of the building damage was collected, which became in an important guidance to evaluate the vulnerability of the constructions.

Basaglia adopted the methodology already used by Vicente (Vicente et al. 2011) to estimate the damage grade of the buildings by combining the GNDT-II (Benedetti & Petrini 1984) procedure, to determine the vulnerability indexes of the buildings (Iv), and the Macroseismic Approach, to determine their vulnerability (V). Basaglia suggested some improvements in the assessment of the vulnerability indexes. He considered the argues suggested by Grimaz (Grimaz 1993), which thought that buildings have usually a non-regular shape and presents different structural characteristics along its different directions. This makes possible to express the vulnerability as a completely different entity dependent also on the inputs characteristics (Basaglia 2015).
Basaglia (Basaglia 2015) has proposed a correction of Formisano method changing both scores and weights, trying to avoid negative values while maintaining as much as possible a similarity with the original method. Suggested form is presented in Table 2.10.

Table 2.10 Proposed revision of additional parameters to the GNDT-II forms for masonry buildings in aggregate (Basaglia 2015).

#	PARAMETERS	CLASSES $C_{v,i}$				WEIGHT
		A	B	C	D	p_i
1	Interactions in elevation	0	15	25	45	1.25
2	Floor plans interactions	0	5	15	45	1.75
3	Presence of offset ceilings	0	25	35	45	0.75
4	Structural of typological heterogeneity	0	10	20	45	1.50
5	Percentage difference within facade openings	0	15	35	45	1.25

Basaglia also proposed a correlation between vulnerability index I_v and Vulnerability V which will be explained in depth in Chapter 3. The results of his work are shown in Figure 2.32 using a GIS map.

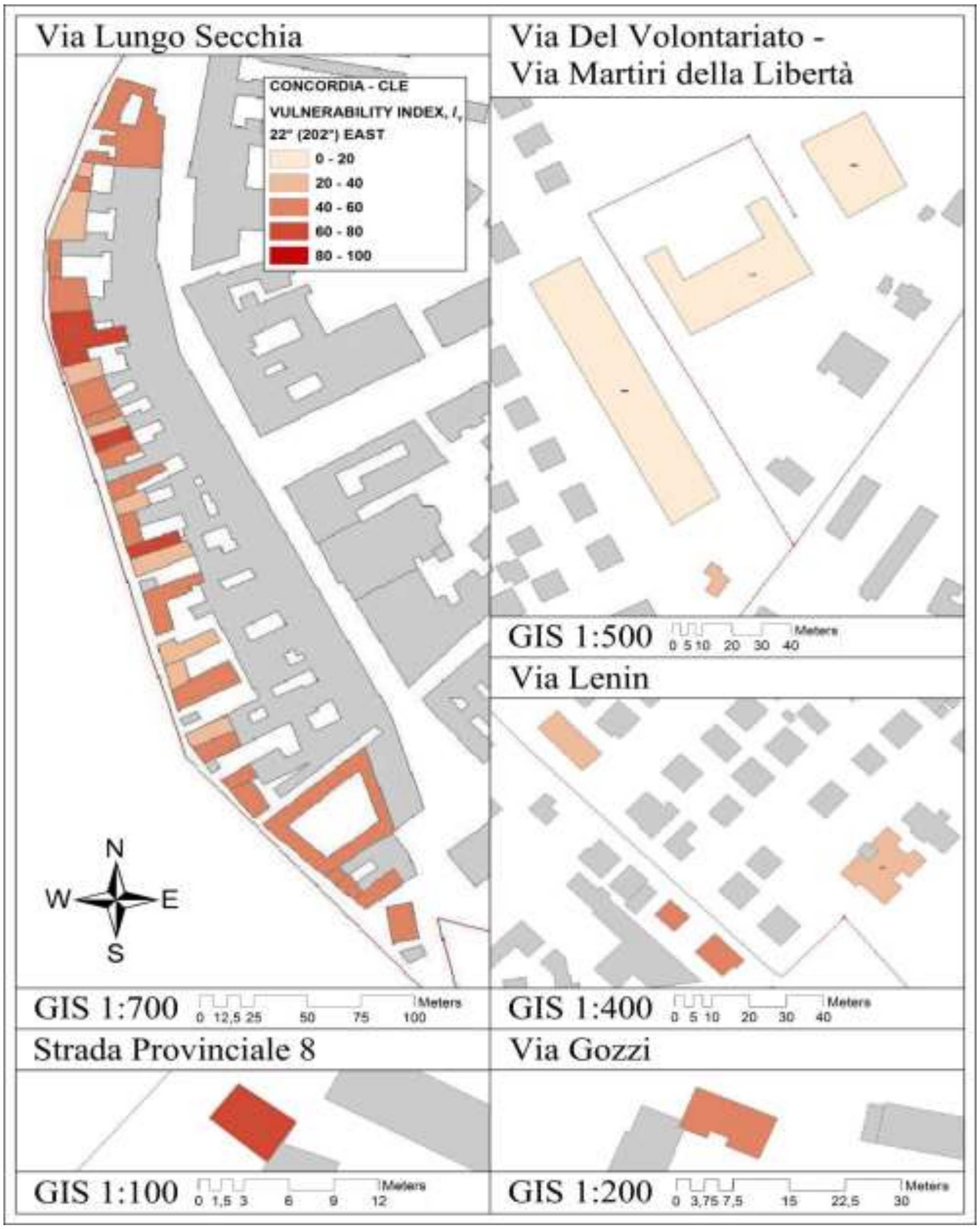


Figure 2.32 Building stock vulnerability map of Concordia sulla Secchia (MO), Italy (Basaglia 2015).

2.7 GEOGRAPHICAL INFORMATION SYSTEM (GIS)

In a study of natural risks, is necessary have the support of sufficient spatial information, as topographic characteristics, geological, hydrological and use of soil. Thereby, it is easier to recognize the most affected zones by using it. Geographical Information System (GIS) represents a multi-purpose tool, which permits to realize the management of this information. It combines with different types of dates, including the database and detailed graphic representation of the obtained results (see Figure 2.33).

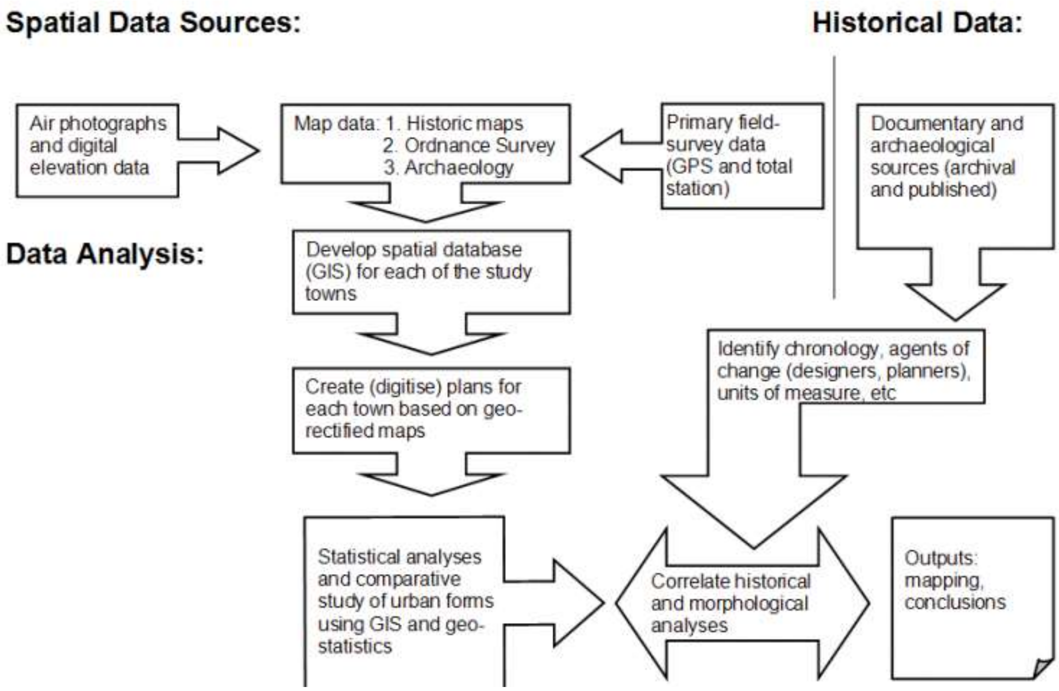


Figure 2.33 Flowchart showing data sources and analysis (Google image).

2.7.1 Concept of GIS

Geographical Information System (GIS) is designed to capture, store, elaborate, analyze and represent the information geographically referenced with the scope to resolve complex problems of planning and management. It also permit to edit dates, maps and reproduce results. GIS works as a database of thematic information, which is associated with a common identification of graphic objects of a digital map. The reason of using GIS is the management of spatial information. The system permits to separate the information in different layers of thematic maps and are kept independent, so to permit to work fast and in a simply way (see Figure 2.34).

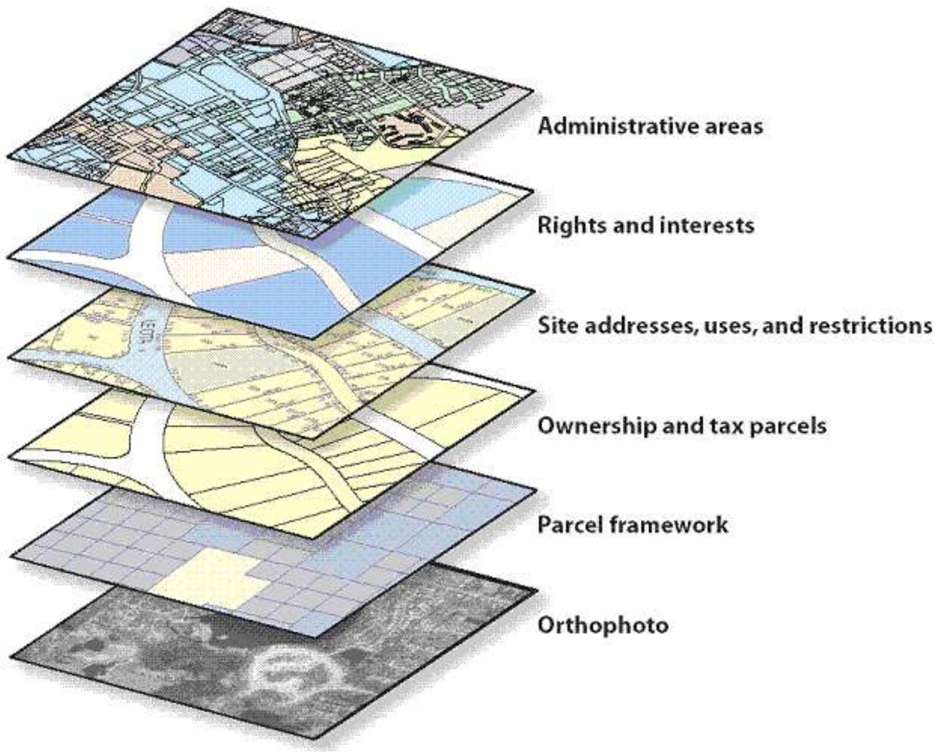


Figure 2.34 Different thematic layers of GIS (Google image).

There are numbers of data that could be displayed and inventoried with the use of GIS or Geographic Information System such as from natural resources, wildlife, cultural resources, wells, springs, water lines, fire hydrants, roads, streams and also houses. The quantities and so the densities of a certain item within a given area could be displayed and calculated. However, there are still many things that you could do with the use of GIS technology.

Here are some of the advantages of using GIS technology:

- It has the ability of improving the organizational integration. GIS would then integrate software, hardware and also data in order to capture, analyse, manage and so display all forms of information being geographically referenced.

- GIS would also allow viewing, questioning, understanding, visualizing and interpreting the data into numbers of ways which will reveal relationships, trends and patterns in the form of globes, maps, charts and reports.
- Geographic Information System is to provide a help in answering questions as well as solve problems through looking at the data in a way which is easily and quickly shared.
- GIS technology could also be integrated into framework of any enterprise information system.
- And there would be numbers of employment opportunities.

Those are among the advantages that could be provided with the use of GIS technology. Considering the use of the said technology might be considered as of great decision to make.

On the other hand, there are as well some disadvantages that might be experienced because of using the GIS technology. And some of those are drawbacks are the following:

- GIS technology might be considered as expensive software.
- It as well requires enormous data inputs amount that are needed to be practical for some other tasks and so the more data that is to put in.
- Since the earth is round and so there would be geographic error that will increase as you get in a larger scale.
- GIS layers might lead to some costly mistakes once the property agents are to interpret the GIS map or the design of the engineer around the utility lines of the GIS.
- There might be failures in initiating or initiating additional effort in order to fully implement the GIS but there might be large benefits to anticipate as well.

With those pros and cons that are mentioned above there will no doubt that there is still of great potential if GIS technology is used apart from the idea of some disadvantages. Now that we are in this generation, the use of GIS technology is indeed of great opportunity to experience its best advantages.

2.7.2 Application of GIS

The possibilities of GIS cover multidisciplinary fields, such as the mapping, the telecom and network services, the transportation planning, environmental impact, disaster management and mitigation, flood damage estimation, soil mapping, in medical field, disaster and business continuity planning, as shown in Figure 2.35.

Figure 2.35 Multidisciplinary fields on using GIS (Google image).

Chapter 3

PROPOSED METHODOLOGY

3.1 INTRODUCTION

Chapter 2 has described the most applied methods to evaluate the seismic risk in large-scale assessment of urban centers. The methodology used in the current research is an empirical model and can be considered as a combination of GNDT-II and Macro-seismic approach.

Previous studies adopted this method to evaluate the vulnerability at urban scale, as discussed in Chapter 2. Vicente (Vicente et al. 2011), used it to assess the vulnerability of Portuguese cities Coimbra and Seixal. Basaglia (Basaglia 2015) also used a similar procedure to assess the seismic vulnerability of Concordia sulla Secchia, Italy. Figure 3.1 represents the stages of this research study that can be classified as follows:

Stage 1: Collect the data of the buildings to be analyzed.

Stage 2: Calculate the Vulnerability index using the GNDT II method.

Stage 3: Define the vulnerability and then define the damage grade.

Stage 4: Define the fragility curves.

Stage 5: Estimate the probabilities of losses (economic and human lives).

Stage 6: Define the seismic scenarios through GIS.

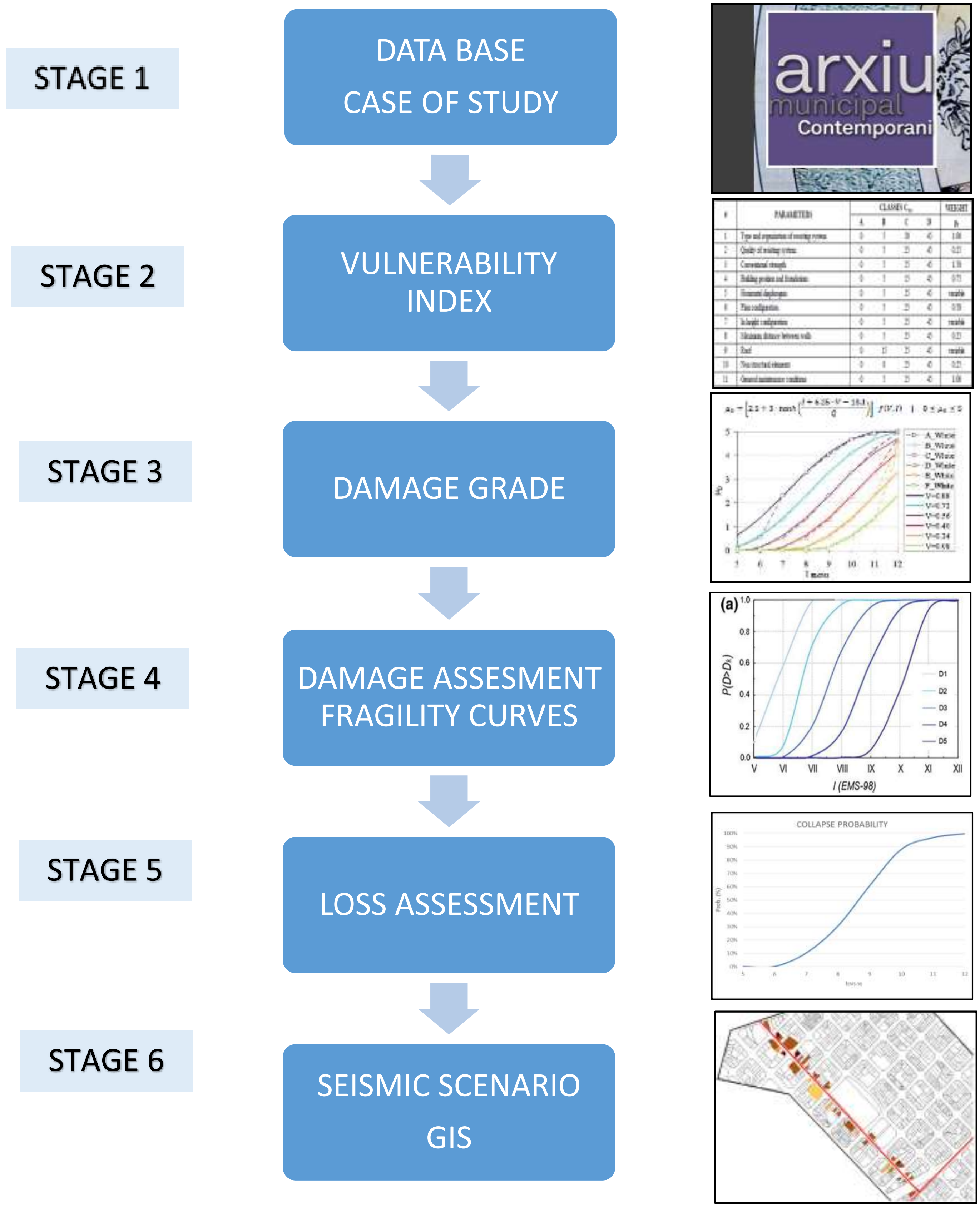


Figure 3.1 Scheme of proposed methodology.

3.2 GNDT-II AND MACRO-SEISMIC COMBINED APPROACH

3.2.1 Data base : Case of Antigua Esquerra de l'Eixample

The first stage consists in the creation of a database of the case of study, which in this case is an important communication axes of the Eixample District of Barcelona (Spain). Detailed information on the design and construction of the buildings in this neighborhood has been obtained by analyzing the archives of the buildings of the city. The main information sources, which were used to obtain the data for the risk assessment at urban scale, are:

- Research in the municipal archive;
- Previous works (PhD/Master theses);
- Territorial information system.

The second stage concerns the procedure of evaluation of the vulnerability index. The procedure followed was the GNDT-II method presented in Chapter 2. The parameters highlighting the most important factors related to the vulnerability index are:

- Resisting system (P1, P2, P3, P4, P8)
- Interaction and irregularity (P6, P7)
- Horizontal resistant elements (P5, P9)
- Non-structural elements (P10)
- State of conservation (P11)

P1 and P2 characterize a building resistant system and govern the structural behavior, evaluating the quality of masonry through the analysis of the constituents (dimension and shape of elements). P3 is one of the most important parameters, since it analyzes quantitatively the resistant capacity using geometric information of the structure. It has the bigger weight (p_i=1.5). P8 is another indicator based on geometric characteristics of masonry building, such as the connection between walls. It indicates in an indirect way the vulnerability of the walls in case of out-of-plane collapse. P8 studies the connection and critical elements in reinforced concrete buildings in order to evaluate their behavior in case of seismic action. P4 analyses the relation between the building and the foundation conditions and the characteristics of the soil.

The second group concerns the interaction between structural irregularities. P6 and P7 evaluate plan and height configurations to evaluate their regularity. The third group includes P5 and P9, which evaluate the horizontal structure, respectively the floor and the roof. P5 evaluates if the floor behaves as a diaphragm and the connections with the wall and P9 evaluates the impulsive nature of roof system above resistant walls in masonry buildings. In case of reinforced concrete buildings, P9 is concentrated on the study of low ductility elements in order to individuate the weak points of the structure. P10 studies the presence of non-structural elements and connection conditions with the principal structure that can worsen the damage level under a seismic action. P11 figures out the present structural fragilities in order to give an evaluation of the state of conservation.

3.2.2 Evaluation of vulnerability index

The second stage consist on calculating vulnerability indexes of Villarroel Street. The Tables 3.1 and 3.2 show each class for each parameter having different weights.

Table 3.1 GNDT-form for masonry buildings (GNDT 1993).

Parameters		Class C_{vi}				Weight	Vulnerability index
		A	B	C	D	p_i	
P1	Type and organization of resisting system	0	5	20	45	1.00	$I_V^* = \sum_{i=1}^{11} C_{vi} \cdot p_i$
P2	Quality of resisting system	0	5	25	45	0.25	
P3	Conventional strength	0	5	25	45	1.50	
P4	Building position and foundations	0	5	15	45	0.75	
P5	Horizontal diaphragms	0	5	25	45	variable *	Normalization: $0 \le I_V \le 100$
P6	Plan configuration	0	5	25	45	0.50	
P7	In height configuration	0	5	25	45	variable *	
P8	Maximum distance between walls	0	5	25	45	0.25	
P9	Roof	0	15	25	45	variable *	
P10	Non structural elements	0	0	25	45	0.25	
P11	General maintenance conditions	0	5	25	45	1.00	

Table 3.2 GNDT-form for RC buildings (GNDT 1993).

Parameters		**Class C_{vi}**			**Vulnerability index**
		A	**B**	**C**	
P1	Type and organization of resisting system	0	-1	-2	$I_V^* = \sum_{i=1}^{11} C_{vi}$
P2	Quality of resisting system	0	-0.25	-0.5	
P3	Conventional strength	0.25	0	-0.25	
P4	Building position and foundations	0	-0.25	-0.5	
P5	Horizontal diaphragms	0	-0.25	-0.5	Normalization:
P6	Plan configuration	0	-0.25	-0.5	
P7	In height configuration	0	-0.5	-1.5	**a)** if $I_V^* > -6.5$,
P8	Connections and critical elements	0	-0.25	-0.5	$I_V = -10.07 \cdot I_V^* + 2.5175$
P9	Low ductility elements	0	-0.25	-0.5	
P10	Non structural elements	0	-0.25	-0.5	**b)** if $I_V^* < -6.5$,
P11	General maintenance conditions	0	-0.5	-1	$I_V = -1.731 \cdot I_V^* + 56.72$

A proposal of improvement of the GNDT II method has been proposed in this research. Urban buildings have usually irregular shapes and present different structural configurations along their different directions. The vulnerability of a generic structural entity can be considered as the sum of two groups of factors: the isotropic and anisotropic ones (Grimaz 1993). The isotropic factors consist in all the characteristics not related to the input direction, such as the building's material and age. The anisotropic factors, on the other hand, include all traits depending on the input direction, e.g. the construction's resistance and the influence of boundary conditions.

Evaluating the vulnerability index in two principal directions, the total vulnerability trend can be approximately represented in function of the orientation of an ellipse having the axes proportional to the vulnerability indexes calculated for the two main directions (see Figure 3.2). Therefore, the vulnerability is represented as a directional characteristic.

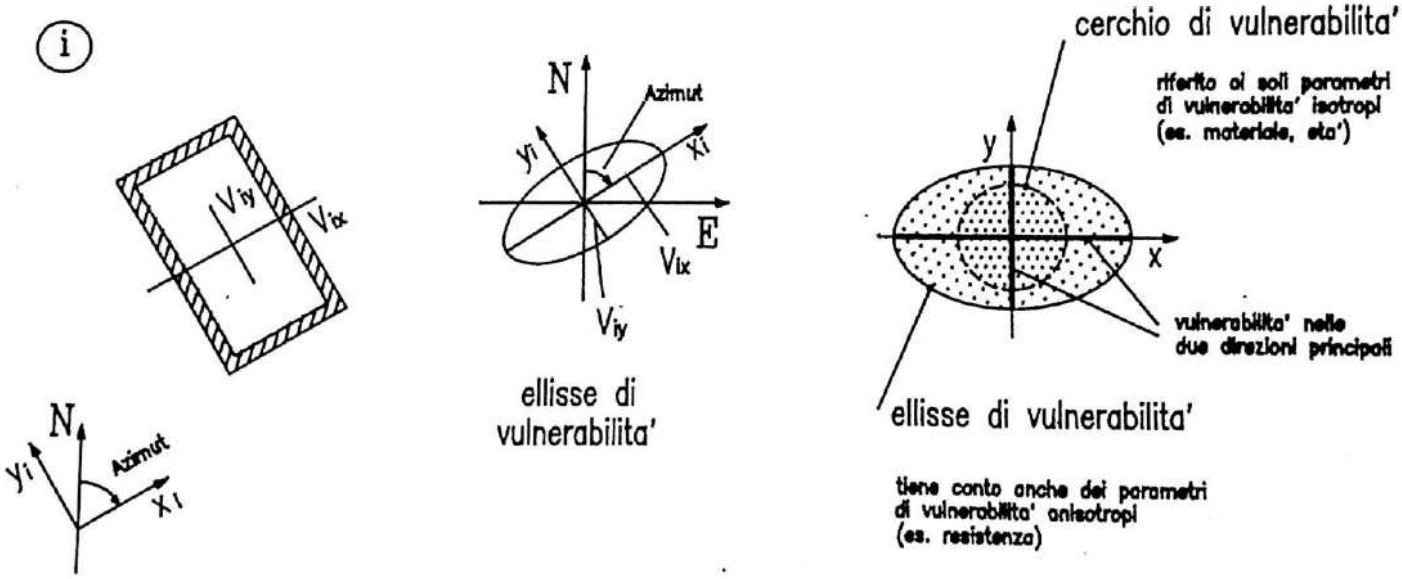


Figure 3.2 Definition of vulnerability ellipse (Basaglia 2015).

The vulnerability indexes described in Table 3.1 and Table 3.2 are calculated referring only to the most vulnerable direction. A method to take into account building characteristics changing the input's direction has been proposed by Basaglia (Basaglia et al. 2016) on the basis of the previous work by (Grimaz et al. 1996). The present research also considers a similar approach in order to evaluate correctly the directional effects of the earthquake on the buildings of the urban centre.

The first step consists in determining the main directions of every building taken in exam, evaluating also the inclination referring to cardinal axes, N-E, unique for the entire city (see Figure 3.3).

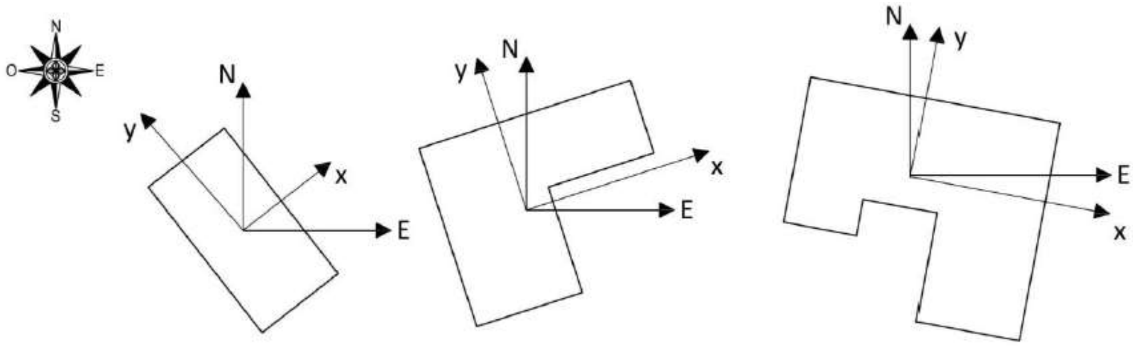
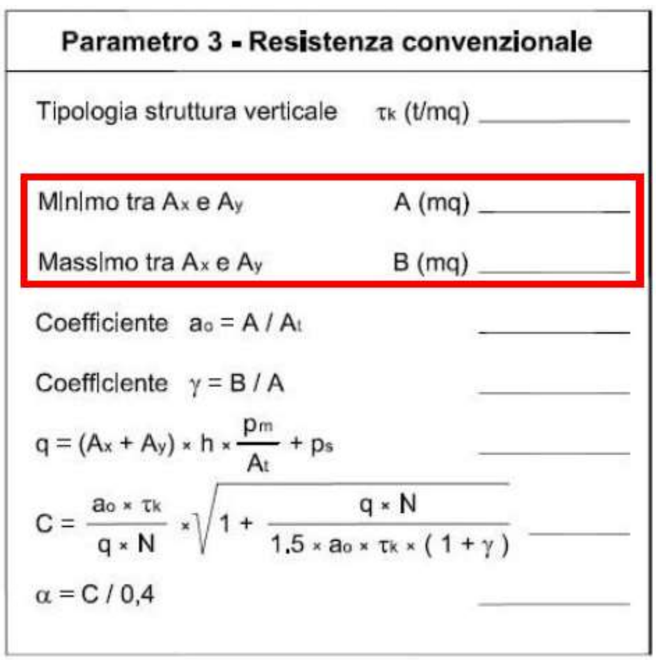


Figure 3.3 Vulnerability ellipse determination, Step 1 (Basaglia 2015).

The next step considers the calculation of the vulnerability indexes I_x and I_y. The original GNDT-II form (see Annex A) is considered but "splitting" the Parameter 3 (Conventional Strength, see Figure 3.4) along the two principal directions of the building.



Parametro 3 - Resistenza convenzionale

Tipologia struttura verticale τ_k (t/mq) ________

Minimo tra A_x e A_y A (mq) ________

Massimo tra A_x e A_y B (mq) ________

Coefficiente $a_o = A / A_t$ ________

Coefficiente $\gamma = B / A$ ________

$q = (A_x + A_y) \times h \times \frac{p_m}{A_t} + p_s$ ________

$C = \frac{a_o \times \tau_k}{q \times N} \times \sqrt{1 + \frac{q \times N}{1,5 \times a_o \times \tau_k \times (1 + \gamma)}}$ ________

$\alpha = C / 0,4$ ________

Figure 3.4 GNDT-II form, Parameter 3 (GNDT 1993).

Instead of using the minimum/maximum value, two conditions are considered as shown in Equations 3.1, 3.2.

$$I_X \rightarrow \begin{cases} A = A_X \\ B = A_Y \end{cases} \tag{3.1}$$

$$I_Y \rightarrow \begin{cases} A = A_Y \\ B = A_X \end{cases} \tag{3.2}$$

The third step consists in determining the vulnerability ellipse. By considering the semi-axes of the ellipse along the principal directions of the building x, y equal to the vulnerability indexes I_x and I_y, and by calling the building's inclination towards the EAST (see Step 1), the implicit equation of the rotated ellipse is shown in Equation 3.3

$$\frac{(x \cdot \cos\alpha + y \cdot \sin\alpha)^2}{Ix^2} + \frac{(y \cdot \cos\alpha + x \cdot \sin\alpha)^2}{Iy^2} = 1 \tag{3.3}$$

The ellipse will be ideally positioned in the building's center, see Figure 3.5.

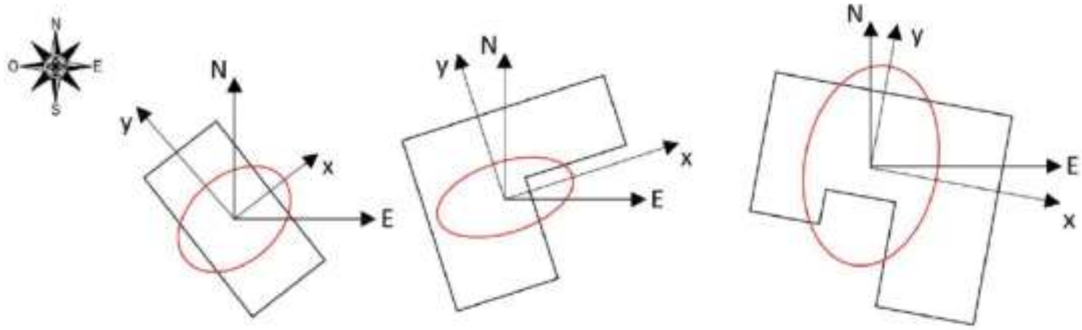


Figure 3.5 Vulnerability ellipse determination, Step 3 (Basaglia 2015).

The following step consists in considering a random direction for the expected earthquake (see Figure 3.6). A vulnerability index is obtained, which depends on the angle of the earthquake direction. This procedure will be applied for angles from 0º to 360º direction in order to provide an overall view of the city vulnerability.

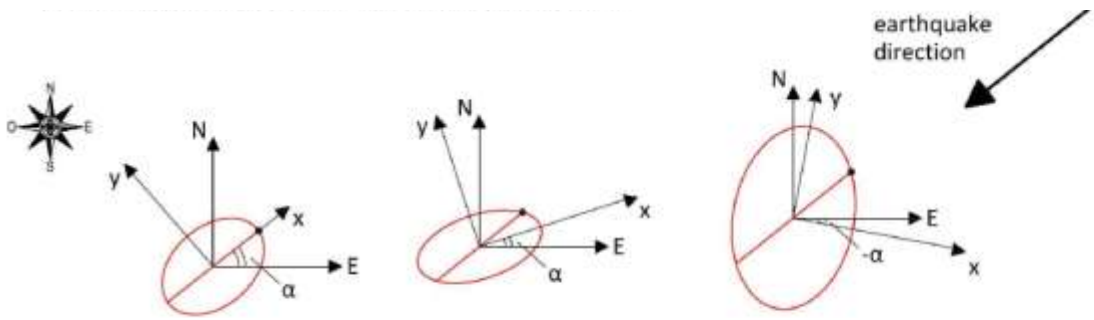


Figure 3.6 Vulnerability ellipse determination, Step 4 (Basaglia 2015).

By mapping all the vulnerability ellipses, it is possible to plot an overview on the urban settlement's global response to a seismic event. There could be areas in fact where the ellipses' sizes are significantly different along different directions, i.e. directions with higher/lesser vulnerability. Having all the vulnerability ellipses it is possible determine the worst seismic scenario. At the end of this stage all the vulnerability indexes are defined. However, there are some considerations to do for masonry buildings.

The GNDT method, which is chosen to calculate the vulnerability index shown before, is developed for isolated masonry buildings. However, most of them are usually built in 'aggregates' in the urban centres. Therefore, masonry buildings collaborate each other and the possible interaction between adjacent buildings should be considered. Therefore, a seismic analysis of such structural complexes has to take into account the possible interaction between adjacent buildings.

The effect of the buildings' aggregates was taken into account in this study following the approach proposed by Formisano (Formisano et al. 2011) and refined later by (Basaglia 2015), as discussed in Chapter 2. It is noticeable that all modified scores according to the followed approach have resulted in the same range of the GNDT-II form, while weights have all increased a little. Applying this correction to account for the aggregate effect, the vulnerability index have not varied too much.

3.2.3 Evaluation of the vulnerability and damage grade

The third stage is the most complicated. The damage grade (μ_D) is expressed in terms of the Vulnerability. The GNDT II method, which is used in this research, is based on the evaluation of the Vulnerability Indexes of the buildings. The first problem we have to deal with is to find a correlation between the Vulnerability and the Vulnerability Index. In this research, a combination between Macro-seismic scale (which is possible define the vulnerability) and GNDT II method (which is possible define the Vulnerability Index) is proposed in order to find a relation to define the damage grade (μ_D).

Macro-seismic methodology is based on the definition of constructive typologies being part of vulnerability classes, classifying the damage and intensity grade according to European macro-seismic scale EMS-98 defined by Grünthal (Grünthal 1998).

Starting from the definition of the damage grade scale (variating from 1 to 5) and their quantitative definition, it is possible to define a damage probability matrix DPM associated to six vulnerability classes (from A to F) as is shown in Table 2.1.

Equation 3.4 defines the vulnerability function for different macro-seismic intensities according to (Giovinazzi & Lagomarsino 2004). It permits to calculate a damage grade μ_D defined from 0 to 5.

$$\mu_D = \left[2.5 + 3 \cdot tanh\left(\frac{I+6.25 \cdot V-13.1}{Q}\right)\right] \cdot f(V,I) \qquad 0 \le \mu_D \le 5 \tag{3.4}$$

Previous researches (Giovinazzi & Lagomarsino 2004) defined numerical values of Vulnerability (V) for each EMS-98 class, as shown in Figure 3.7. The Figure 3.8 shows the vulnerability curves $I_{EMS\text{-}98}$- μ_D using Equation 3.4.

V_A	V_B	V_C	V_D	V_E	V_F
0.88	0.72	0.56	0.40	0.24	0.08

Figure 3.7 Vulnerability values for each EMS-98 class.

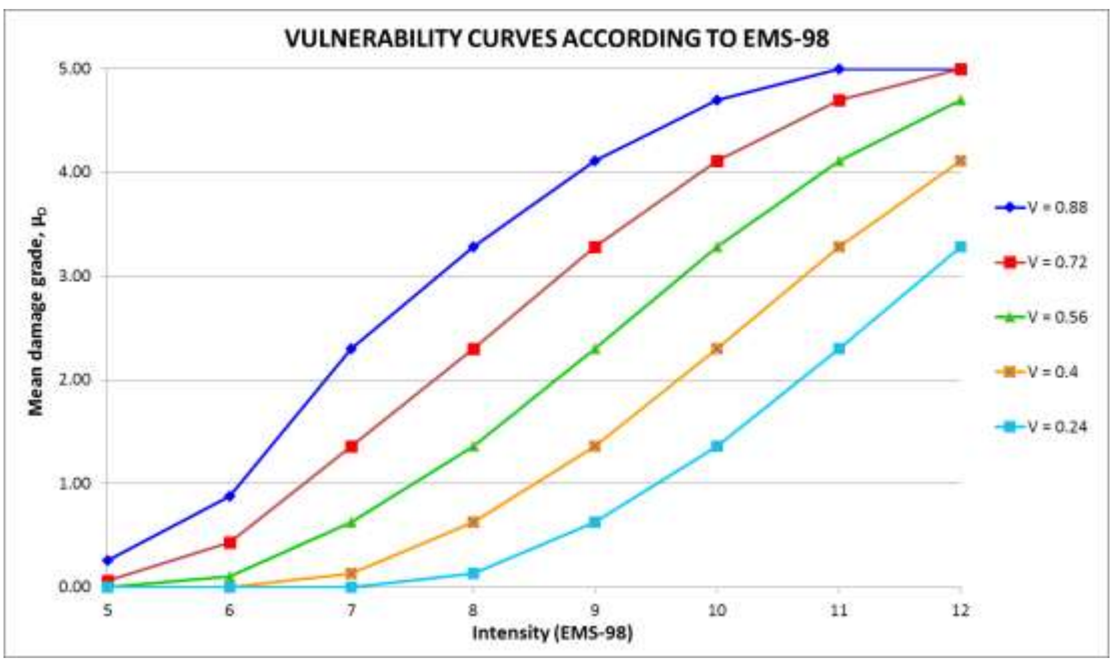


Figure 3.8 Vulnerability curves $I_{EMS\text{-}98}$- μ_D according to EMS-98.

The GNDT II methodology evaluates the vulnerability based on a vulnerability function, considering a relation between seismic action (expressed in PGA terms) and damage level (expressed by an economic index). This correlation is obtained by a vulnerability index, and based by the surveys of damages in different earthquakes happened in Italy. The Figure 3.9 indicates this relation. An initial phase having a light damage y_i (cracking) can be observed, and then followed by a linear branch until y_c, which corresponds to severe and extensive damages, near to the collapse. The evaluation of the damage level is simplified by a trilinear function, by delimitated values of acceleration y_i and y_c, corresponding to the first damage and near of collapse damage respectively.

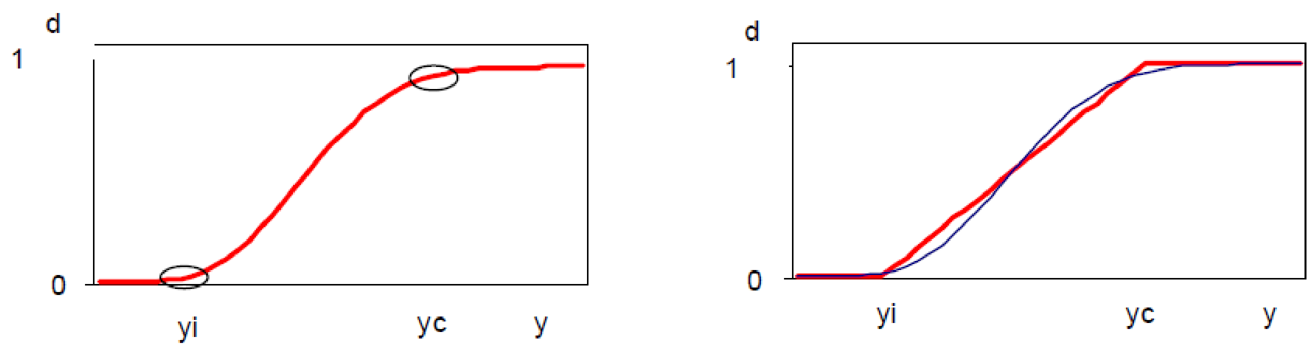


Figure 3.9 Vulnerability function PGA-damage d(y): Qualitative function trilinear (Grimaz 1993).

GNDT II considers peak ground acceleration (PGA) as a parameter to characterize the seismic action. Figure 3.10 represents the vulnerability curves, which permits to evaluate the damage for a determined level of seismic action (characterized by PGA or seismic intensity) for different values of vulnerability.

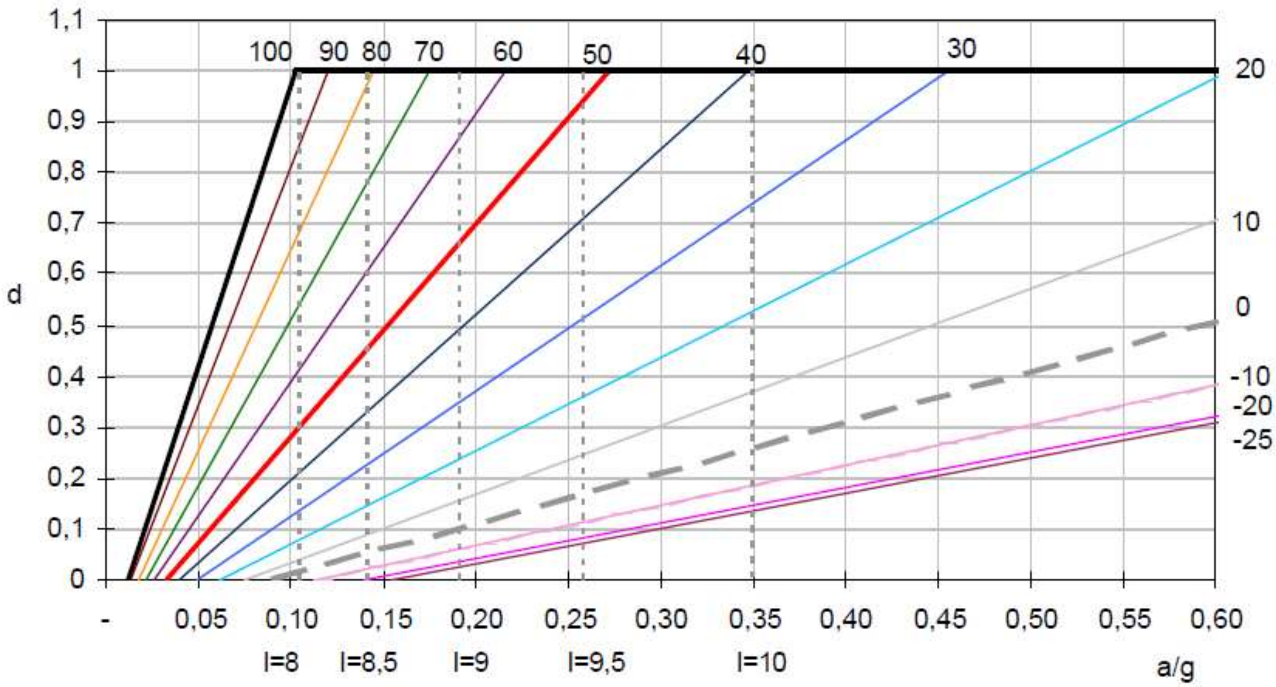


Figure 3.10 Vulnerability functions proposed by Benedetti and Petrini (Benedetti & Petrini 1984).

It is possible establish a logarithmic relation between intensity and correspondent acceleration through the expression proposed by Guagenti and Petrini (Guagenti & Petrini 1989) shown in Equation 3.5.

$$\ln(y) = a \cdot I_{MCS} - b,\ where\ a = 0.602, b = 7.073 \qquad (3.5)$$

Where y represents the peak ground acceleration (PGA); I_{MCS} is the intensity referred in MCS scale; a and b are constants.

The tri-linear curves defined by Benedetti e Petrini (Benedetti & Petrini 1984) of GNDT II methodology can be converted and expressed in PGA terms and in MCS intensity scale by using the Equation 3.6. Margottini (Margottini et al. 1992) proposed a relationship between the intensity I and the PGA, based on the following expressions in terms of MCS and MSK intensities.

$$I_{MSK} = 0.734 + 0.814 \cdot I_{MCS} \quad (3.6)$$

With reference to the study made by Grimaz (Grimaz et al. 1996) a *damage index*, d, is defined, that together with the *vulnerability index* can be used to express the relation between damage, vulnerability and seismic action entity. The approach followed assumes a piecewise linear relation among the acceleration and damage, as shown by Equation 3.7.

$$d(y,d) = \begin{cases} 0 & for\ y \leq y_i \\ \frac{y-y_i}{y_c-y_i} & for\ y_i \leq y \leq y_c \\ 1 & for\ y_c \leq y_i \end{cases} \quad (3.7)$$

Where y is an estimate of ground acceleration empirically derived by intensity; y_i is the value corresponding to the initial occurrence of damage; y_c is the value corresponding to the building's collapse.

Y_i is calculated using the Equations 3.5 and 3.6. For y_i and y_c a mathematical relation with the vulnerability index has been theorized as shown in Equations 3.8 and 3.9.

$$y_i = \alpha_i \cdot \exp(-\beta_i \cdot v) \quad (3.8)$$

$$y_c = [\alpha_c + \beta_i \cdot v^{\gamma}]^{-1} \quad (3.9)$$

Where v is the value of the vulnerability index; α_i, β_i, α_c, β_c and γ are parameters determined in the work by Grimaz using post-seismic data from:

- the 1976 Friuli earthquake, regarding in particular the city centre of Venzone (UD, intensity IX M.C.S.), Tarcento and San Daniele (UD, intensity VIII M.C.S.);
- the 1984 event that struck the Parco d'Abruzzo (AQ, FR, IS, intensity VII M.C.S.) and previous works (see Guarenti and Petrini, 1989).

Numerical values of the factors listed above were determined with the least squares minimization procedure (see Table 3.3).

Table 3.3 Parameters for damage/vulnerability index relation (Grimaz et al., 1996).

α_i	β_i	α_c	β_c	γ
0.08	0.013037	1.5371	0.00097401	1.8087

The damage index obtained in this way can now be converted into the mean damage grade used by the Macro-seismic method. Considering Petrini and Benedetti (Benedetti & Petrini 1984), the damage is estimated in terms of economic damage. This quantity is correlated to the mean damage grade μ_D shown in Equation 3.10.

$$\mu_D = \sum_{k=0}^{5} p_k \times D_k \tag{3.10}$$

Where p_k is the probability associated to the damage grade D_k with k [0 to 5].

Previous studies proposed different correlations between economic damage index and the mean damage grade, i.e. ATC-13 (Applied Technology Council ATC 1985); Bramerini (Bramerini et al. 1995); HAZUS (FEMA 1999); Dolce (Dolce et al. 2003) as shown in Table 3.4.

Table 3.4 Correlations between mean damage grade and economic damage proposed by different authors (Vicente et al. 2011).

Grau de dano, D_k		0	1	2	3	4	5
Nível de dano		Sem dano	Ligeiro	Moderado	Severo	Muito severo	Destruição
Índice de dano económico, d_e	ATC-13 [1985]	0.000	0.050	0.200	0.550	0.900	1.000
	Bramerini *et al.* [1995]	0.000	0.010	0.100	0.350	0.750	1.000
	HAZUS [1999]	0.000	0.020	0.100	0.500	1.000	1.000
	Dolce *et al.* [2000]	0.000	0.035	0.145	0.305	0.800	1.000

This work considers the correlation proposed by the Servizio Sísmico Nazionale (SSN) (Bramerini et al. 1995). The expression is shown in Equation 3.11:

$$\mu_D = 4 \times d^{0.45} \tag{3.11}$$

After defining the transformation of acceleration y to seismic intensity $I_{EMS\text{-}98}$, and the transformation of economic damage index to mean damage grade, it is possible to compare the vulnerability curves of GNDT II with those of Macro-seismic method in I-μ_D terms.

To compare the curves of the two methodologies a central value of damage grade (μ_D =2.5) is considered. The curves are shown in Figure 3.11.

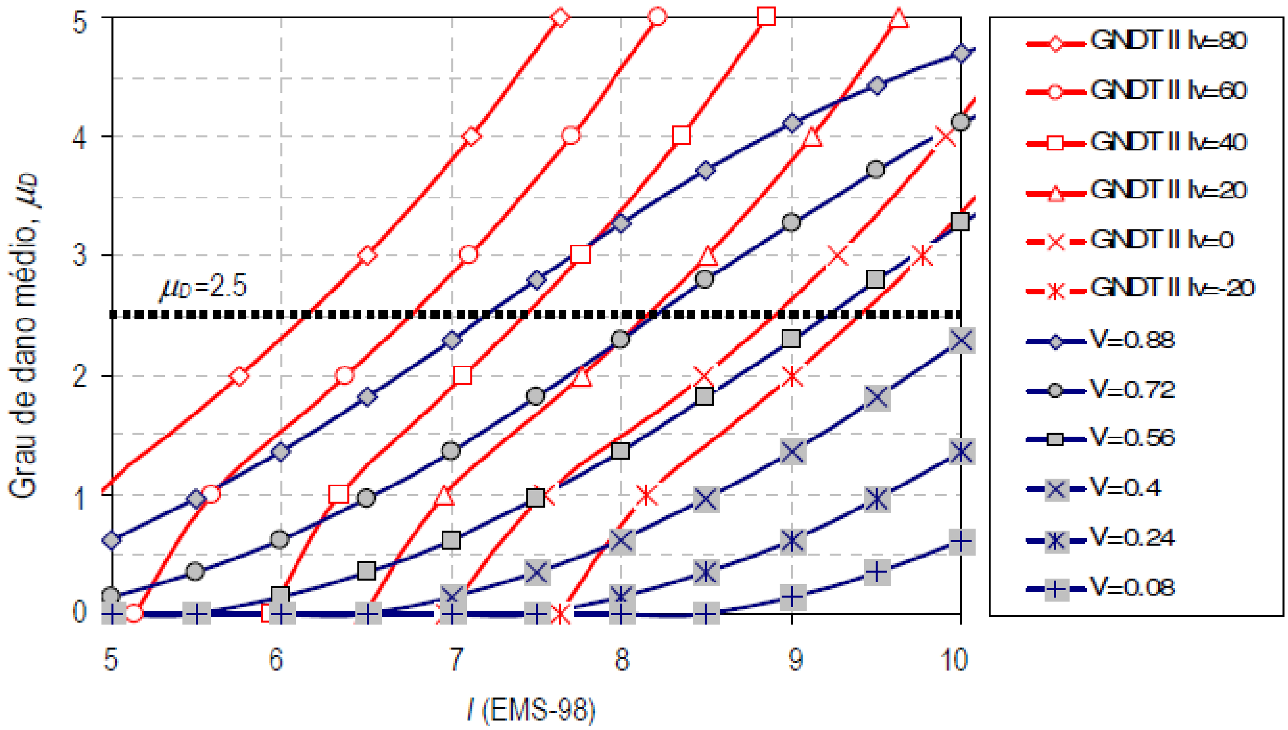


Figure 3.11 Comparison between GNDT and Macro-seismic curves.

This combination between GNDT II (I_v) and Macro-seismic method (V) is expressed by an analytical correlation, which is different for masonry and reinforced concrete. In case of masonry, Vicente proposes the values for the two methods shown in Table 3.5.

Table 3.5 Correlation between the two methodologies for masonry buildings (Vicente et al. 2011)

Metodologia GNDT II	I_v = 45	I_v = 20	I_v = -5
Metodologia macrossísmica	Classe A (V = 0.88)	Classe B (V = 0.72)	Classe C (V = 0.56)

Equation 3.12 establishes the correlation between I_V and V:

$$V = 0.592 + 0.0057 \cdot I_V \tag{3.12}$$

The vulnerability V obtained by the Equation 3.12 will be used to evaluate the damage grade of the buildings.

This is a definitely a strict limitation, as almost every city has constructions of different structural typologies, such as R.C., steel, wooden or mixed. It becomes essential then to find a correlation also for this structural type, to include also R.C. buildings in the vulnerability assessment. Table 2.1 shows that, according to the EMS-98 classification, R.C. buildings are generally included between vulnerability class C and E, and only sometimes in class F. In analogy with the determination of the correlation for masonry buildings then, the study will mainly focus in the interval C-D-E.

At first, μ_D-I curves were recreated for the EMS-98 classes using Equation 3.4 (see Figure 3.12). Then the three I_v values that best fit the corresponding vulnerability curves have been figured out through Equations 3.7, 3.8, 3.9 and 3.10. Results are shown below in Table 3.6.

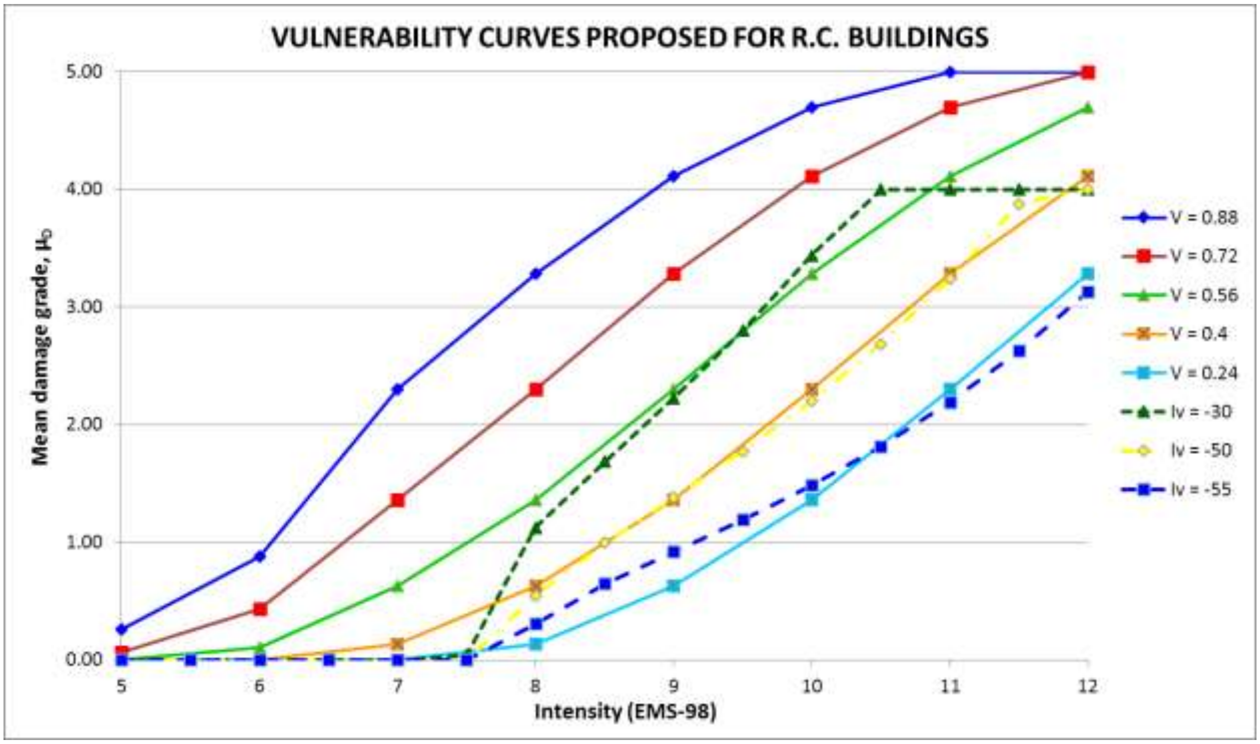


Figure 3.12 Comparison between GNDT and Macro-seismic curves for RC buildings (Basaglia 2015)

Table 3.6 Correlation between the two methodologies for RC buildings (Basaglia 2015)

Macroseismic method	Class C (V = 0.56)	Class D (V = 0.40)	Class E (V = 0.24)
GNDT-II level	I_V = -30	I_V = -50	I_V = -55

The analytical correlation between between I_V and V is finally expressed in Equation 3.13 according to Basaglia (Personal Communication).

$$V = 0.2825 + 0.0135 \cdot I_V - 0.00003333 \cdot I_V^2 \tag{3.13}$$

3.2.4 Evaluation of the fragility curves

The following stage is focused on calculating the probability of exceeding the damage grade and then plotting it in function of vulnerability to obtain histogram curves, and in function of Intensity to obtain fragility curves. Once the vulnerability has been defined, the mean damage grade can be computed for each macro-seismic intensity, using Equation 3.4. From these values then, using a probabilistic approach it is possible to determine damage distribution histograms for different events of varying seismic intensity and their respective vulnerability index. Most frequently applied methods are based on the binomial probability mass function PMF (see Equation 3.14) or the beta probability density function PDF (see Equation 3.15):

$$PMF: p_k = \frac{n!}{k!(n-k)!} \cdot \mu_D^k \cdot (1-\mu_D)^{n-k} \qquad n \geq 0 \quad 0 \leq p \leq 1 \tag{3.14}$$

Where p_k is the probability of having k-level of damage (k=0:5); n is the maximum damage level (n=5 in this case).

$$PDF: p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \cdot (x-a)^{r-1} \cdot (b-x)^{t-r-1} \qquad a \leq x \leq b \;\; a=0, b=5 \tag{3.15}$$

Note: the PDF is defined in the interval [0:1].

In the current research, the beta distribution function was adopted, since previous works showed that it is the most versatile. In fact, it allows to “control” its shape via the geometric parameters. In this way it enables the fitting even for very narrow and broad damage distributions (Giovinazzi 2005).

Assuming that a=0 and b=5, eq. 8 can be simplified to (see Equation 3.16)

$$p_{\beta}(x) = k(t,r) \cdot x^{r-1} \cdot (5-x)^{t-r-1} \tag{3.16}$$

Where, for a continuous variable x, both the variance (σ_x^2) and mean value (μ_x) are related to t and r as defined in Equations 3.17, 3.18:

$$t = \frac{\mu_x(5-\mu_x)}{\sigma_x^2} - 1 \tag{3.17}$$

$$r = t \cdot \frac{\mu_x}{5} \tag{3.18}$$

As parameter t presents a reduced variation in the numerical damage distributions, it is reasonable to adopt a unique value, t=8 to represent the variance of all possible damage distributions. Based on this assumption, the Equation 3.19 becomes:

$$r = 8 \cdot \frac{\mu_D}{5} \tag{3.19}$$

Probability histograms of specific damage grade P (D_k=d) are derived from the difference of cumulative probabilities: where are determined in the Equation 3.20:

$$P(D_k = d) = P_D[D_k \geq d] - P_D[D_{k+1} \geq d] \tag{3.20}$$

Where P (D_k) are determined as in the Equation 3.21:

$$P(D_0) = p(0) = \int_0^{0.1} k(t,r) \cdot x^{r-1} \cdot (5-x)^{t-r-1} dx$$

$$P(D_k) = p(k) = \int_{\frac{k}{5}-0.1}^{\frac{k}{5}+0.1} k(t,r) \cdot x^{r-1} \cdot (5-x)^{t-r-1} dx \tag{3.21}$$

$$P(D_5) = p(5) = \int_{0.9}^{1} k(t,r) \cdot x^{r-1} \cdot (5-x)^{t-r-1} dx$$

Besides histogram, a continuous and better way of visualize damage is using *fragility curves*.

Similarly, to vulnerability curves, they describe the relationship between earthquake intensity and damage, but through conditional cumulative probability, P (D_k), see Figure 3.13.

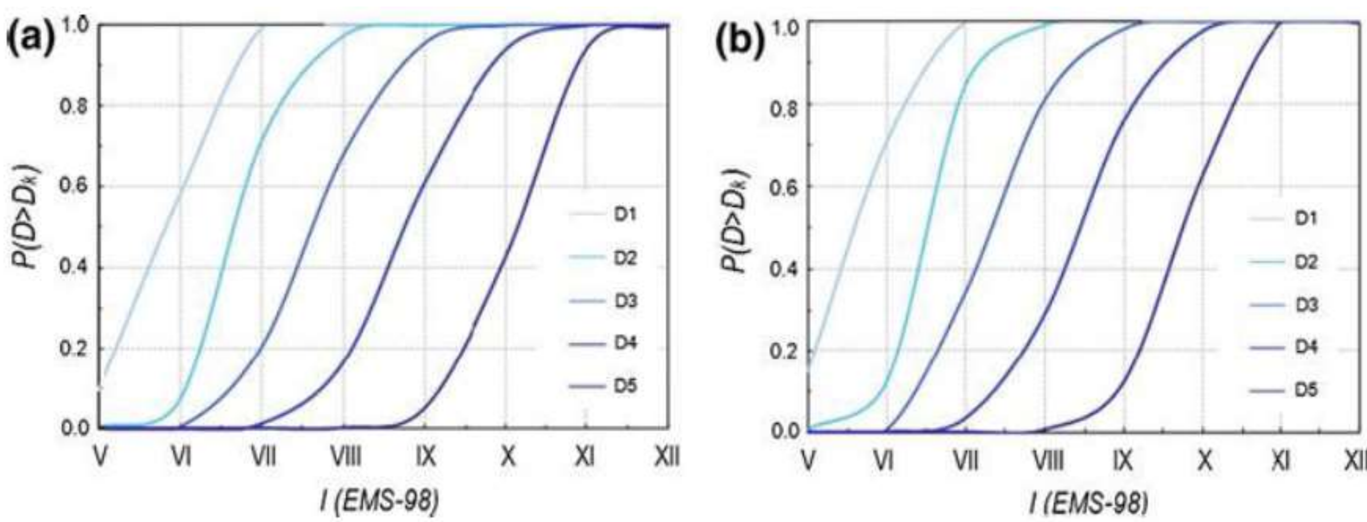


Figure 3.13 Examples of fragility curves for two different vulnerability indexes (Vicente et al. 2011).

3.2.5 Loss assessment

An important stage is the following where it is calculated the probability of losses in different points of view. Probabilities obtained can be finally used for a seismic loss assessment. At first equations have been derived to evaluate collapsed and unusable buildings (see Equations 3.22 and 3.23).

$$P_{collapse} = P(D_5)$$

$$N_{collapse} = N_{buildings} \cdot P_{collapse} \tag{3.22}$$

$$P_{usuable\ buildings} = P(D_3) \cdot W_{ub,3} + P(D_4) \cdot W_{ub,4}$$

$$N_{unusable\ buildings} = N_{buildings} \cdot P_{unusable\ buildings} \tag{3.23}$$

Where $W_{ub,3}$ and $W_{ub,4}$ are weights indicating the percentage of buildings associated with the damage level D_k, that have suffered collapse or that are considered unusable. The most frequently used values are $W_{ub,3}$=0.4 and $W_{ub,4}$=0.6, referring to the work by Bramerini (Bramerini et al. 1995).

Nevertheless, the most serious consequence of an earthquake are always casualties and the main goal of all risk mitigation strategies is to ensure human safety. Therefore, the number of dead and severely injured and homelessness can be estimated using the Equations 3.24 and 3.25.

$$P_{dead\ and\ severely\ injured} = 0.3 \cdot P(D_5)$$

$$N_{dead\ and\ severely\ injured} = N_{occupants} \cdot P_{dead\ and\ severely\ injured} \tag{3.24}$$

$$P_{homeless} = P(D_3) \cdot W_{ub,3} + P(D_4) \cdot W_{ub,4} + P(D_5) \cdot 0.7$$

$$N_{homeless} = N_{occupants} \cdot P_{homeless} \tag{3.25}$$

3.2.6 IMPLEMENTATION OF THE RESULTS INTO THE GEOGRAPHICAL INFORMATION SYSTEM (GIS)

The last stage consists in producing the visual outputs of the research, i.e. the seismic scenarios maps using the GIS instrument. Visual representation of vulnerability assessment results in a large-scale map as a useful method for showing a global overview of potential effects of the seismic event. The implementation of the information into the *Geographic information System* (GIS) represents an important stage of the research, since the GIS is capable to handle, gather, store, analyze and elaborate output results with the geographical data. An important step of the last stage is to implement risk assessment plans.

The last stage of the methodology, aims to suggest critical paths to facilitate the elaboration of the risk mitigation plans to safeguard the vital lines of the cities. Therefore, it will be necessary to carry out critical analysis of the urban morphology of the case of study, and recognize the strategic nodes, routes, buildings and areas that could be considering decisive in cases of disasters. For these step, *The Manual for the Analysis of the Emergency Limit Condition*, ELC (2004) will be considered.

The output data could be used to implement strategic plans, applied in different fields and scales. In a deeper assessment, the results can be used to identify the most vulnerable buildings and propose procedures and techniques to improve the seismic resistance of the buildings typologies.

Chapter 4

APPLICATION TO THE EIXAMPLE DISTRICT OF BARCELONA, SPAIN

4.1 INTRODUCTION

Barcelona is a densely populated city and the most of the city's building stock was built without using seismic design criteria. The combination of old buildings constructed without seismic criteria and a highly populated and active city can be extremely risky under the effects of even a moderate earthquake. Recently, these facts have awakened the need for a seismic risk assessment for the city.

The focus of the present study is the evaluation of the seismic risk of a neighborhood of the Eixample district of Barcelona. For this aim, it is necessary to know the urban area from a global point of view which is. In the following paragraphs information about geotechnical characteristics, historic evolution of the city, territorial organization, typology building construction and population distribution is presented.

Recent studies of the seismic damage to unreinforced masonry buildings of Barcelona have confirmed their vulnerability and highlighted the need for assessment of each building's seismic demand and response (Lantada et al. 2009; Barbat et al. 2006; Pujades et al. 2012). By completing this assessment, damage scenarios and plans can be developed to reduce the risk.

4.2 BARCELONA CITY

Barcelona is the capital city of the autonomous community of Catalonia in Spain and, after Madrid, is the second largest city in Spain. Catalonia is located at NE of Spain and is bordered by France and Andorra to the north and the Mediterranean Sea to the east. Barcelona is located between two rivers: the Llobregat River at the western and the Besos River at the eastern part. The Tibidabo-Collserola Mountains, about 500 m high border its northern part and the Mediterranean Sea limits its southern part. Figure 4.1 shows the location of Barcelona in a map.

Figure 4.1 Map of Barcelona, Catalonia, Spain (Google map).

Barcelona had an estimated population of 1.63 million in 2014, concentrated in an area of 100 km^2, with a density of 15,991 per square kilometers. The city is organized in 10 districts (see Figure 4.2) and is surrounded by bordering cities which form a dense metropolitan area where live nearly 5 million of habitants.

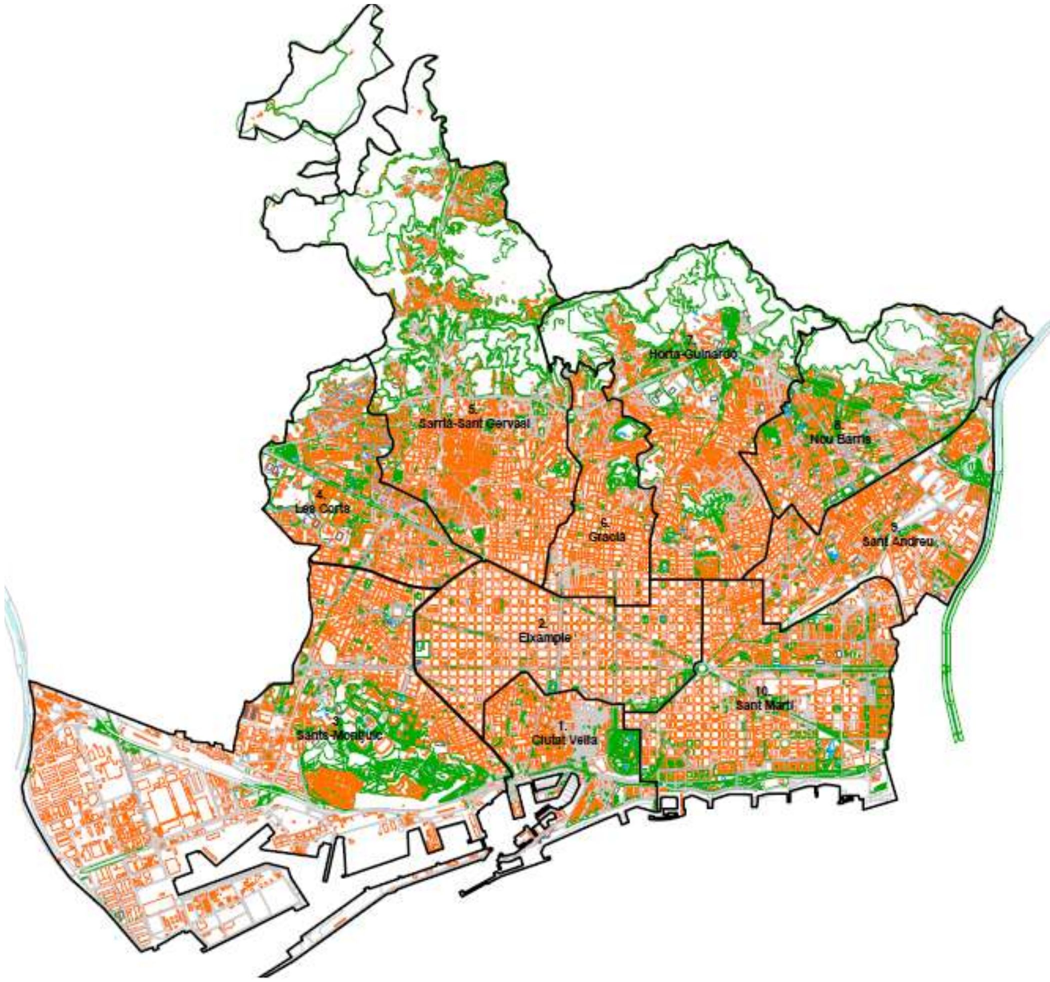


Figure 4.2 Subdivision of Barcelona in districts (Ajuntament of Barcelona).

4.2.1 History of Barcelona

The first human signals in Barcelona are aged 2,500 years, but the Romans arrived Barcelona 218 years before Jesus Christ. The historical evolution of Barcelona includes the following periods: pre-roman, Roman (218 BX, 250 AX), Christian (250-717), Arab (718-803), Carolinian (803-1000), Comptal (1000-1200), Barcelona head of Catalonia (1200-1516), Barcelona of the Austrians (1516-1714), and Barcelona of the Bourbons (1714-1868). At the end of the Roman period the city had between 10,000 and 12,000 inhabitants and at the end of the 4th century, Barcelona was a fortified town with a very big wall 8 m high, 3.65 m width and more than 1,122 m long. The surface covered by the city was about 10.50 Ha. At the beginning of the 11th century, Barcelona had about 20,000 inhabitants and occupied about 80 Ha. Four centuries later Barcelona had about 115,000 inhabitants and in 1850, 175,000 people were leaving there. In Barcelona, during the first half of XIX century the urbanization of the intern of the city was intensified, having the aspect of a modern city. Between 1858 and 1868 there were demolished the walls of the city and was started a great urbanistic project to construct modern Barcelona, a new open city and industrial. What happened in Barcelona was the actual l'Eixample neighborhood, which was designed by engineer Ildefons Cerdà.

The project of expansion of the city permitted to join the center of the city with the other villages, which are the districts, and the neighborhoods of the actual city. The approbation of 'Plan of Eixample' of Barcelona by Ildefons Cerdà in 1859 changed and converted the Catalan city into a referent of urbanism.

The census of 1900 established that the number of habitants was 553.000. By 1909 and 1929, Barcelona experienced a colossal expansion, having 1.005.565 in 1930. By 1940 and 1960, the number of habitants grew highly (see Figure 4.3).

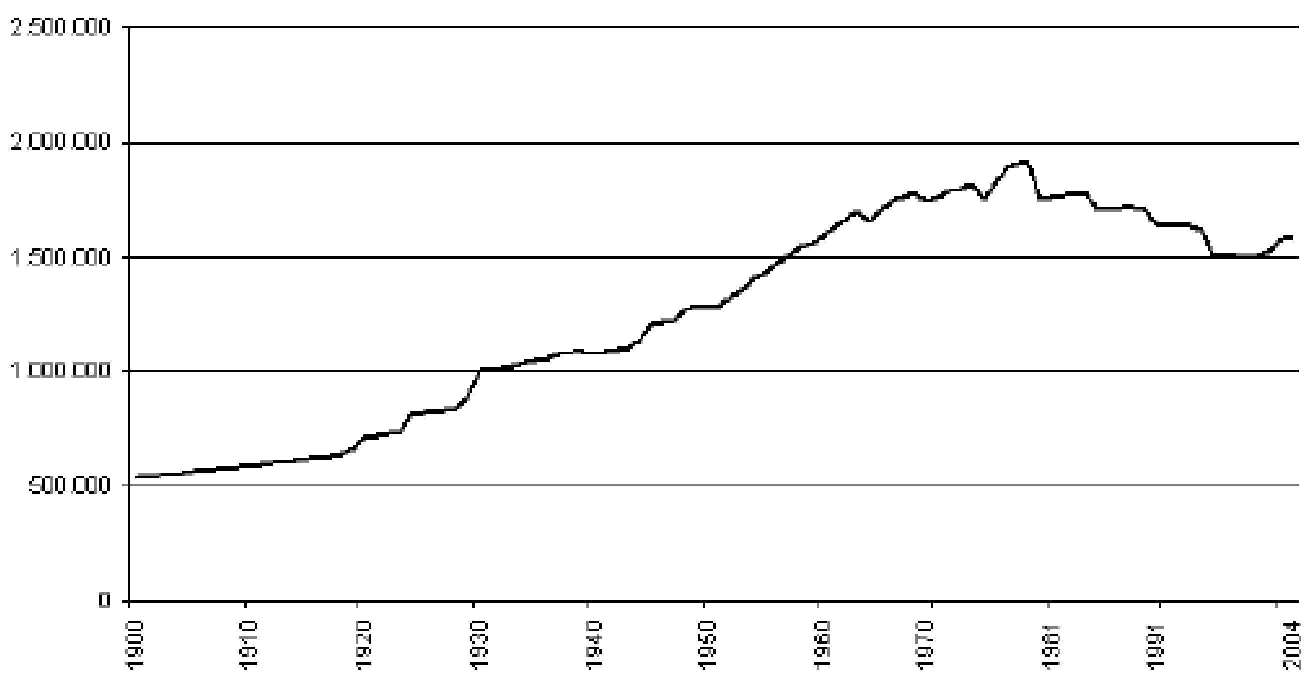


Figure 4.3 Population evolution of Barcelona since 1900 (Ajuntament of Barcelona).

Actually, mountains of Montjuic and Collserola, and the river Besos, which limit the increment on the surface leaving as only opportunity the reconstruction of unused areas, limit Barcelona. The last examples of transformation were the Vila Olimpica in 1992 and opening to the sea of the Avenida Diagonal with Forum Universal de les Cultures in 2004. The district of Eixample is one of the principal areas of Barcelona were it is concentrated an important number of population, with a noticed economic activity and important cultural heritage.

4.2.2 Geology Characteristics

The city of Barcelona is located in the NE of Iberic peninsula, extended between the deltas of Llobregat and Besos River. According to geomorphological point of view it is clearly visible two different areas: the mountain which consist a rock basement with Paleozoic materials and tertiary and plain created by quaternary (Cid et al. 2001).

Two main geomorphologic units compose the soils of the city: the mountain relieves and the plain. The mountains are Paleozoic and Tertiary materials that outcrop in the north (Tibidabo Paleozoic Mountain) and in the SE (Montjuic Tertiary Mountain). Most part of the extension of the city is located by the plain of Barcelona, distinguishing the presence of detritus at the upper side and deltaic materials near Besos and Llobregat River. Some anthropic soils exist in several areas of the city; mainly in the southern beaches (see Figure 4.4).

- Tibidabo-Collserola (Paleozoic slates and granites)
- Montjuïc (Tertiary marls, sands and conglomerates).
- Tricycle deposits (Pleistocene).
- Llobregat delta (Holocene sands and silts).
- Besós delta (Holocene sands and silts).

– Anthropic soils.

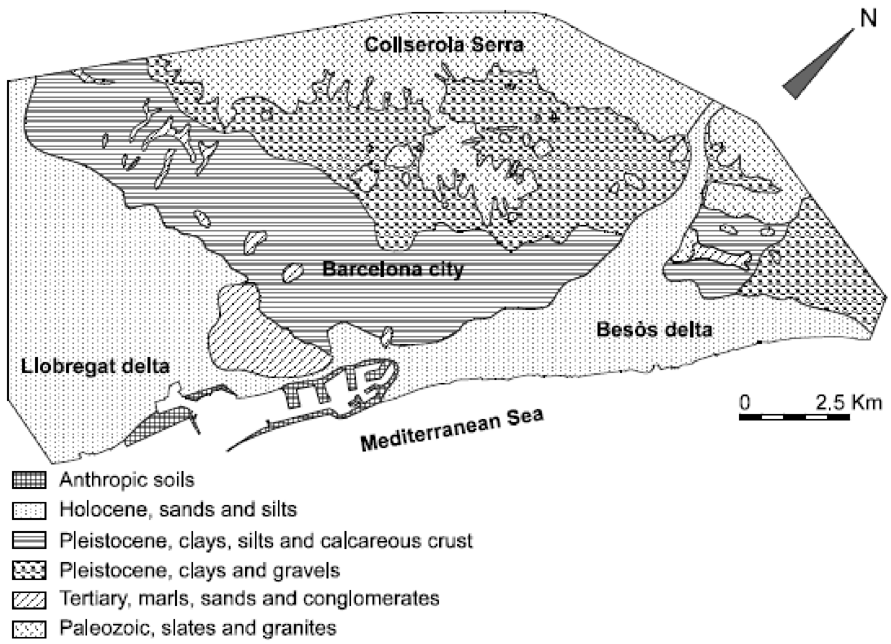


Figure 4.4 Geological map of Barcelona region (Cid et al. 2001).

4.2.3 Tectonics and seismicity

The Occidental Mediterranean is located in a zone of collision between European and African tectonic plate. Catalonia has a moderated seismicity and presents low tectonically deformation compared with the other regions nearby, like Italy or Greece. According to the studies of Secanell (Secanell et al. 2004) the seismicity of Catalonia is represent by three big unities: The Pyrenees, The Mediterranean and Cuenca del Ebro. The most of the earthquakes occurred at the Pyrenees area. These earthquakes were perceive widely in Catalonia with a maximum of intensity VI-VII in the Barcelona city (Secanell et al. 2004). Although it was not possible to have instrumental data, the descriptions of the effects founded in historical documents permitted to estimate the Macro-seismic intensity ((Olivera et al. 1994)). The seismicity of the Catalonia region is moderate when compared to other regions of the Mediterranean Sea. Between the 14th and 15th centuries, the seismic activity reported in Catalonia was over its usual average and several earthquakes caused damages in Barcelona. On February 2, 1428, an earthquake in the Pyrenees with a local magnitude of 6.5 and an epicentral distance of 90 km damaged some churches in Barcelona, like Santa Maria del Mar, whose collapse of the rose window caused 25 casualties. In 1448, another earthquake with a local magnitude of 5.5 cracked a wall in a castle. During the 20th century, few earthquakes were felt in the city with a maximum intensity of IV degrees in the MSK intensity scale.

Deterministic seismic hazard was evaluated based on the historical earthquakes that had affected the city of Barcelona (Irizarry et al. 2011). The historical earthquakes of Girona in 1428 (I = IX) and Cardedeu in 1448 (I = VIII) were chosen as reference earthquakes. On May 15, 1995, a small earthquake (M≈4.6) occurred in the Mediterranean offshore of Catalonian and shaked the city (MSK intensity IV) producing an unusual reaction of the population: the telephones of civil protection and mass media were collapsed.

In order to design a seismic emergency plan scientific and civil institutions are working together to evaluate the seismic risk of the city. Seismic hazard, soil response and building vulnerability have been analyzed. Preliminary studies on lifelines and special buildings also have been performed. All the collected information is being implemented in a Geographic Information System (GIS) to obtain damage scenarios for the city (see Figure 4.5).

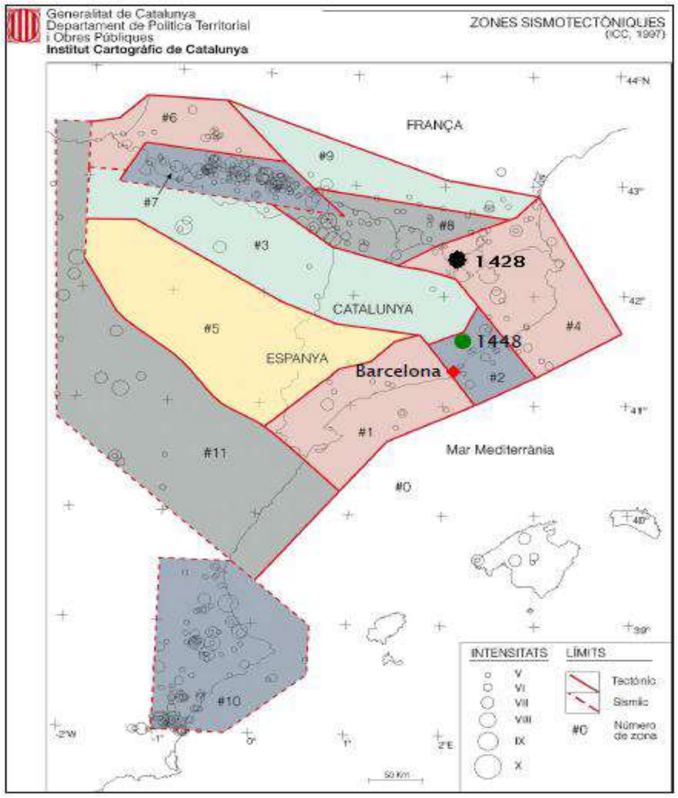


Figure 4.5 Reference earthquakes location (Irizarry et al. 2011).

Some factors as high density of population, building with high vulnerability and the presence of materials as Holocene-Pleistocene can produce a considerable amplification of seismic effects. Many dynamic parameters are necessary to simulate numerically the ground effect: propagation of seismic waves, the velocity of waves, maximum dynamic modulus, density and thickness.

During the last 10 years the Cartography Institute of Catalonia developed several studies to have much more clear definition about seismic risk of Catalonia, revising historic Macro-seismic information and updating instrumental data (Secanell et al. 2008; Cid et al. 2001). Secanell (Secanell 1999) carried out a detailed analyses about hazard and seismic risk of Catalonia considering also the amplification caused by local effects. Cid (Cid et al. 2001) carried out a detailed analyses about seismic zonation soil for the city of Catalonia. The final scheme proposed by Cid classifies the soil of the city in four types, which corresponds in four big zones (see Figure 4.6).

Zone I: Holocene outcrop with a velocity Vs = 200 for depth superior of 20 m.

Zone II: Pleistocene outcrop with tertiary substrate having a thickness sufficient big to influent the respond. The velocity of the waves is Vs = 300 m/s.

Zona III: Pleistocene outcrop without a tertiary substrate having a thickness sufficient big to influent the respond.

Zona R: Rock outcrop (Paleozoic and Tertiary).

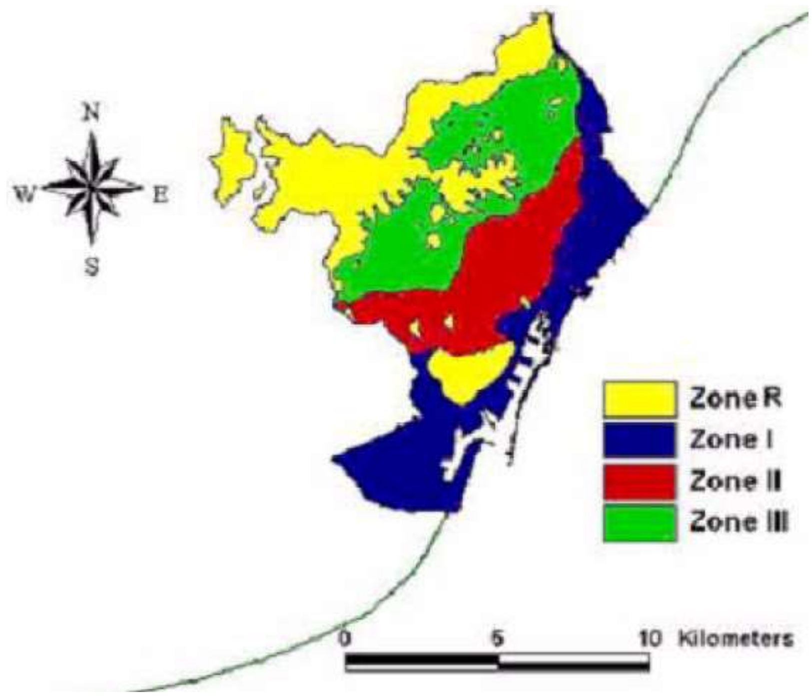


Figure 4.6 Seismic zonation of Barcelona (Cid et al. 2001).

The expected seismic MSK intensity in Barcelona for a 500 years return period is about VI-VII (Secanell 1999). The corresponding PGA level is about 0.03g and 0.07g. This values are very similar but slowly greater than the proposed ones in the Spanish seismic code (NCSE-94 1994).

4.2.4 Seismic code in Spain

The application of design codes can carry a reduction of seismic risk in urban areas. Seismic codes present recommendations about seismic load that should be used in design, methods of structural analysis, criteria that should be applied to assure a good global behavior. The code of Fomento Ministry (NCSE-02 2002) is currently used in Spain, an actualization of the previous code of 1994 (NCSE-94 1994).

In current code, it is established that for a return period of 500 year the basic acceleration expected in Spain is between 0.04g and 0.24g. At the specific case of Catalonia, the acceleration vary between 0.04g and 0.14g. Barcelona is located at a moderate seismic zone and the basic acceleration value is 0.04g. The Table 4.1 resume the historic evolution of the code and presents a classification of three protection levels: no code, pre-code and with code in base of period construction of buildings. The 'Normas Basicas de la Edificacion NBE' were established by the Real Decreto 1650/1977 by *Ministero de la Vivienda*, and defined the necessary regulation for design and execution of the buildings.The current seismic code NCSE-02 substituted the NCSE-94 on October 2002 and extended the application to all the types of constructions. The NCSE-02 code established the referent method for seismic analysis of a structure using response spectrum, in combinationwith modal analysis. In addition, it permits the evaluation of dynamic response using a numerical integration of the equation of motion.

Table 4.1 Construction periods based on the existence of a seismic code (Barbat et al. 2006).

Periodos constructivos	Zonas sísmicas	Zonas no sísmicas
Antes de 1962	Sin norma	Sin norma
1962: MV-101 (1963)	Pre-Norma	Pre-Norma
1968: PGS-1 (1968)	Con Norma	Pre-Norma
1974: P.D.S. (1974)	Con Norma	Pre-Norma
1995: NCSE-94 (1995)	Con Norma	Pre-Norma
2002: NCSE-02 (2002)	Con Norma	Pre-Norma

4.3 CASE OF STUDY: ANTIGA ESQUERRA DE L'EIXAMPLE

The *Eixample*, which means the enlargement in Catalan, is one of ten districts of the city of Barcelona. It is one of the most representative districts of Barcelona, located in the central part of the city. The construction of this district took place between 1860 and 1950 and the buildings were designed only for vertical static loads without careful considerations of seismic design criteria.

In 1856, the engineer Ildefons Cerdà presents at 1:5000 scale, a topographic project map of the city of Barcelona, called Eixample (the enlargement). Cerdà simplified the complicated system into a basic unit. The blocks are shaped as octagon, which are called "Manzana", with empty space inside and open street space outside (see Figure 4.7). Every Manzana was designed in accordance with the mathematical rule in a strict way. The length of every single side was 113m and that of the hypotenuse of the corner (angle of 45 degree) was 20m.

Figure 4.7 Urban texture made by typical "Manzana" of Eixample (Google map).

Besides, each block had a square courtyard with 50×50 m^2. Meanwhile, in order to ensure good ventilation and lighting to courtyard, Cerdà set a rule that buildings located within the Manzana should have a maximum building height of 22m (see Figure 4.8). Corresponding to a limit of six stories for the buildings and a height to width ratio of approximately 1:1 for 20m wide streets. Changes in the bylaws in the 1930s and 1940s allowed the increase in the building height limits over the six floors and the construction of one or two additional penthouse levels setback from the street.

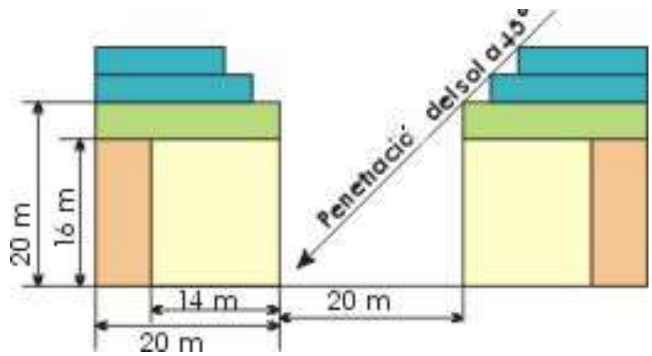


Figure 4.8 Rules of construction made by Cerdá (Google image).

4.3.1 Building construction systems

In general, the buildings of the Eixample district are part of aggregates, forming building blocks. Important differences in the number of storeys and in the level of the floors are frequent within a block. Adjacent buildings either can be separated or may have a common wall and this characteristic may increase their seismic vulnerability. According to the official statistics of Barcelona corresponding to the year 2001, Barcelona has about 700,000 housings and 69,000 buildings, with an average of about 2.24 inhabitants in each.

The unreinforced masonry buildings of Barcelona are tall and have openings of considerable size in their walls. This characteristic affects their vulnerability, as well as the long and thin walls without perpendicular stiffening (see Figure 4.9 and Figure 4.10). All these particular features, typical for the constructive techniques of the city at that time, have been identified as potential damage sources. The floors of these unreinforced masonry buildings are made of timber, steel or precast concrete beams with small ceramics vaults in between, according to the building period, showing a reduced in-plane stiffness both to bending moment and to axial forces (see Figure

4.11) Almost all of these buildings have two soft storeys, due to the greater height of their first two floors (Castellò & Mañà 2003) (see Figure 4.12).

Furthermore, cast iron columns were used in many buildings instead of masonry walls at the base and ground floors, reducing even more their lateral stiffness, because their upper and lower edges are not perfectly clamped. Overall, many buildings of the Eixample district have to be classified in the highest vulnerability class of the European Macro-seismic Intensity Scale, EMS-98.

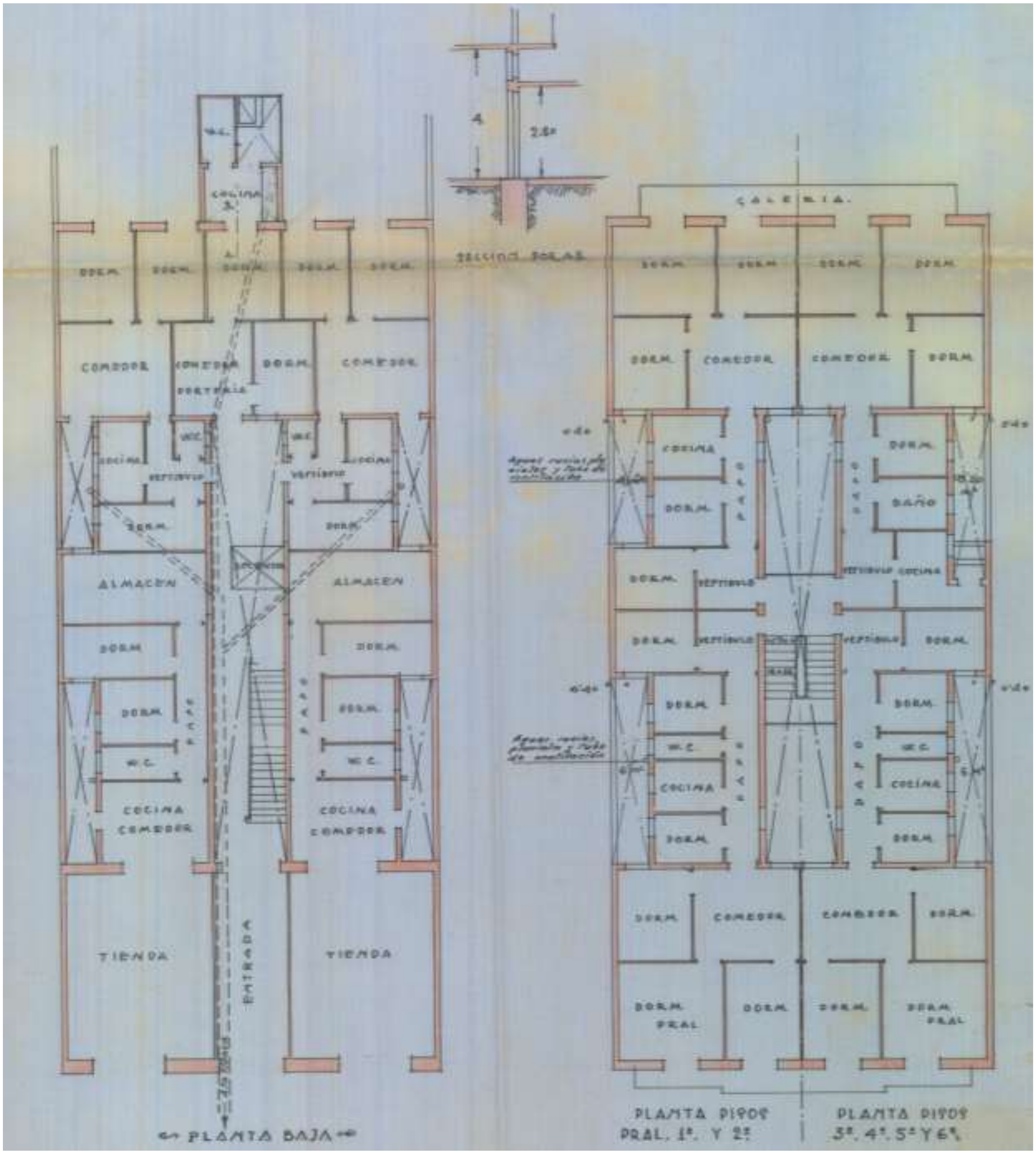


Figure 4.9 Floor plans of masonry building of Villarroel Street 231.

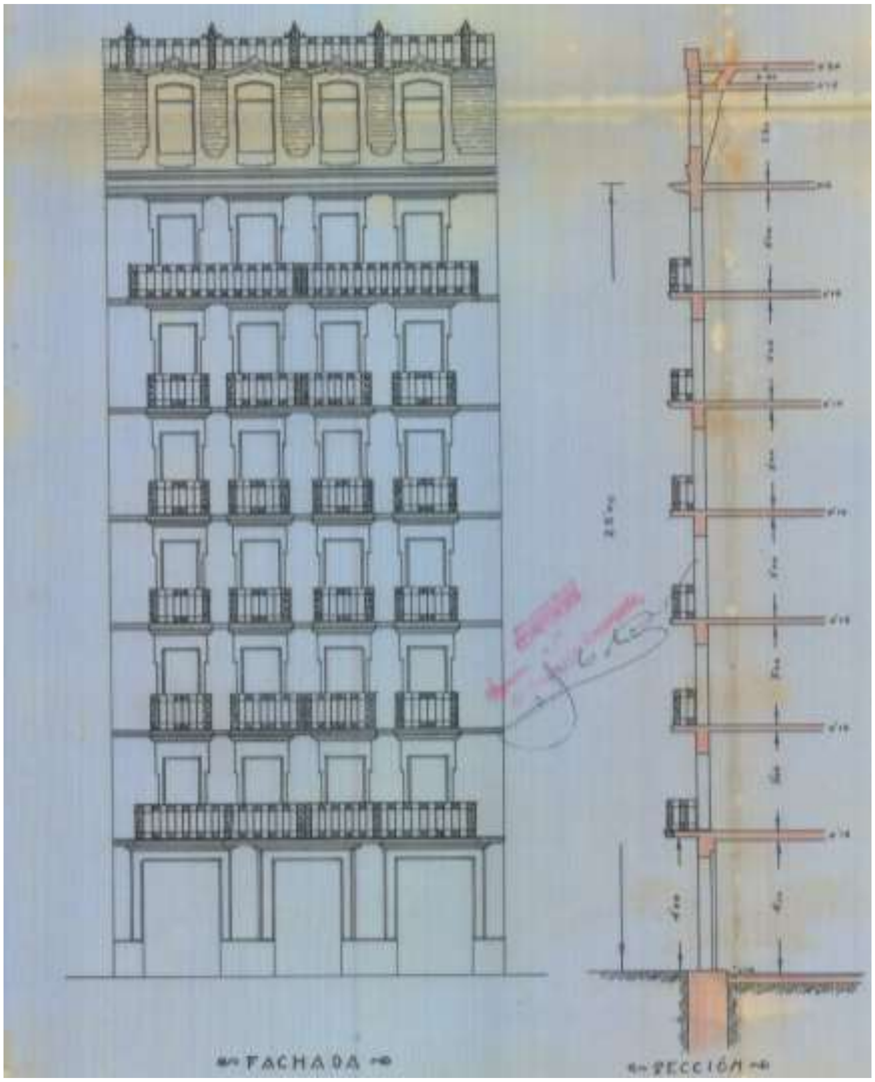


Figure 4.10 Facade and Section of masonry building of Villarroel Street 231.

a)

b)

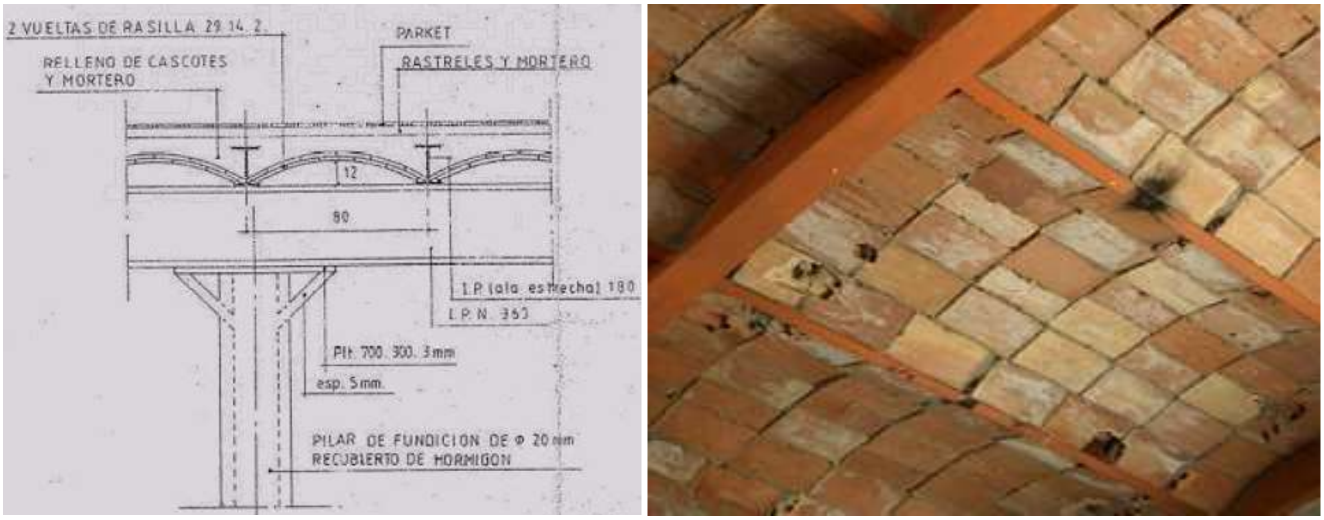


Figure 4.11 Floor plans examples of unreinforced masonry: a) ceramic block and timber beam system b) ceramic block and steel beam system [Google image].

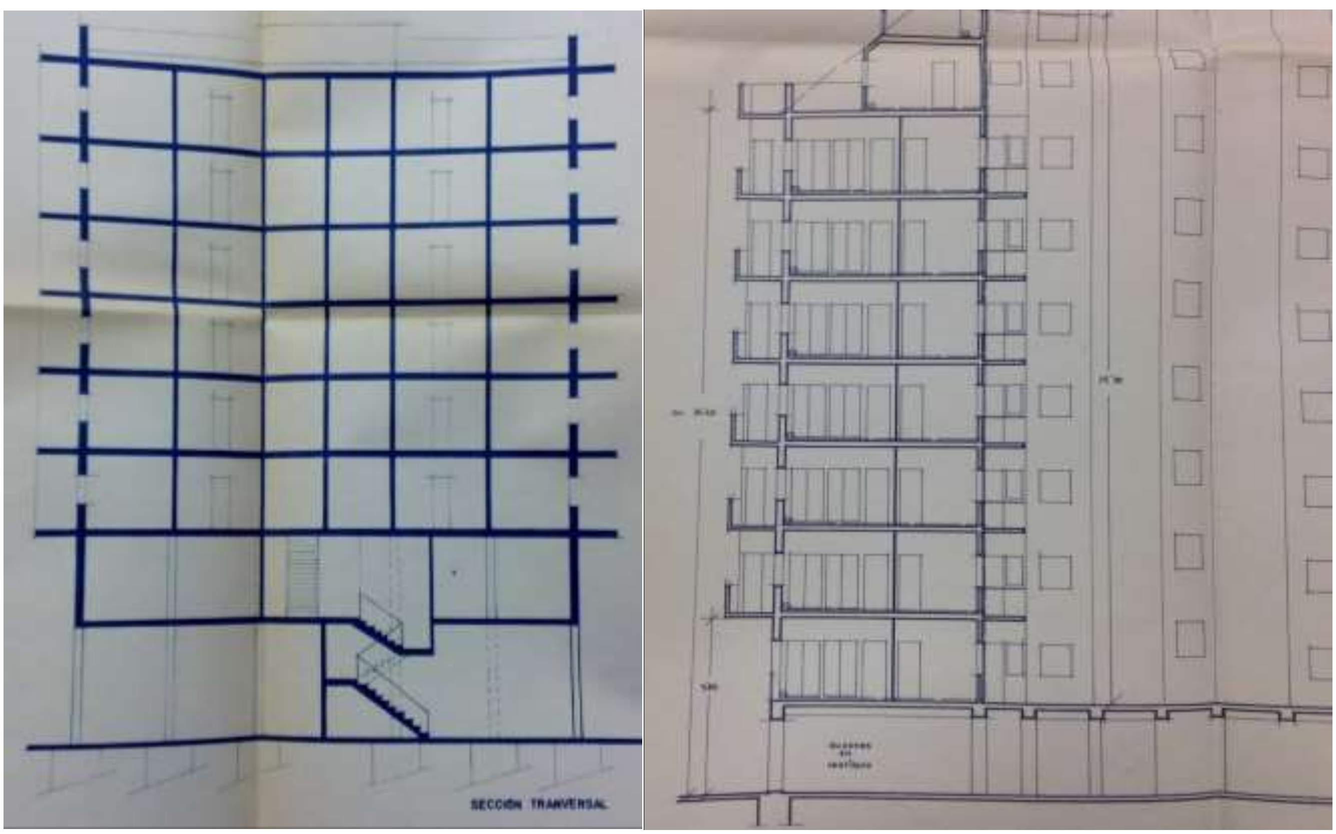


Figure 4.12 Examples of pilotis buildings of Eixample.

Since the middle of the twentieth century, the number of reinforced concrete buildings increased significantly in Barcelona, becoming nowadays the most frequent typology. Most of the reinforced concrete buildings of Barcelona are not moment resisting frames, but they consist of columns and slabs in their waffled-slab floors version, which is a structural type not adequate for seismic areas due to their low ductility (see Figure 4.13). Most of them also have a soft first storey. The Spanish code limits their ductility factor to 2, while many earthquakes, like that of Kokaeli, Turkey, 1999, have dramatically shown the high seismic vulnerability of this kind of buildings. In the seismic areas of Europe, the seismic design of reinforced concrete buildings varies extremely and structures show a large variation of earthquake resistance. Accordingly, the EMS-98 scale assigns a very wide range of vulnerability to the framed reinforced concrete buildings used in Europe, which covers the whole vulnerability range from buildings without earthquake resistant design to buildings design with high-level seismic codes. The reinforced concrete buildings of Barcelona fall within the high vulnerability part of the EMS-98 scale, for which significant damage for relatively low seismic intensities is expected.

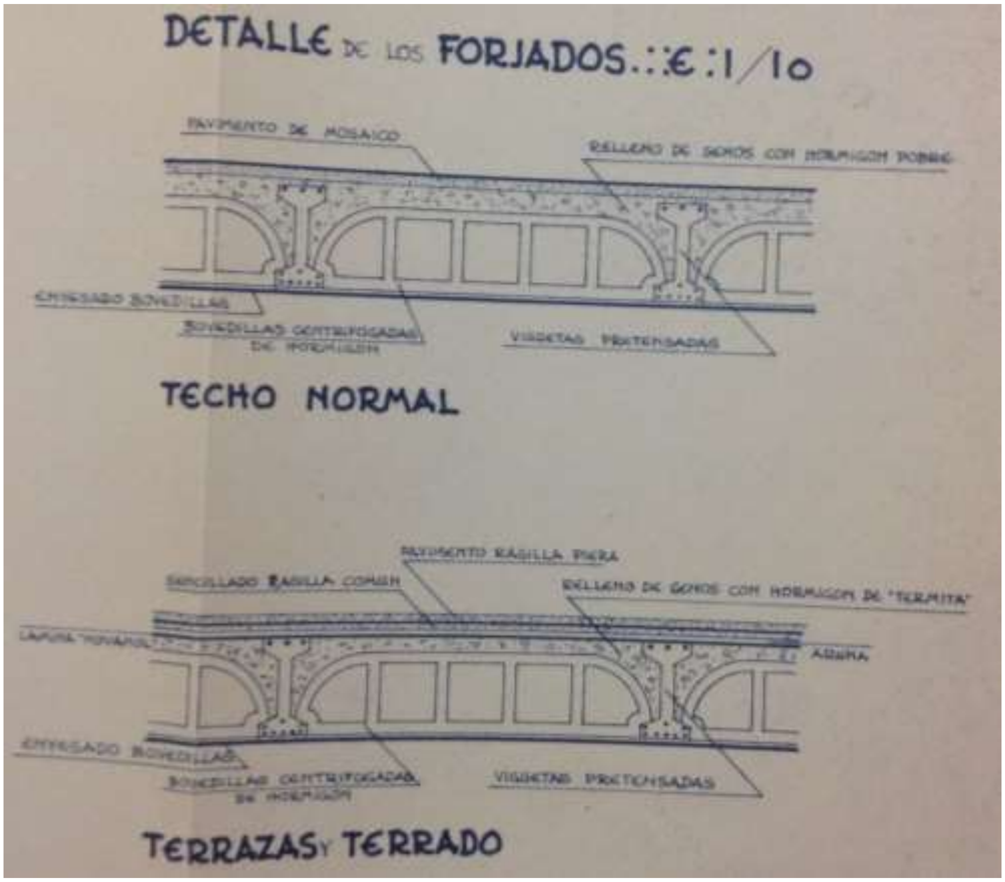


Figure 4.13 Slab-floor typology of reinforced concrete building of Villarroel Street 187.

4.4 DETERMINATION OF ELC SUB-SYSTEM OF ANTIGA ESQUERRA DE L’EIXAMPLE, BARCELONA

This study consists in the seismic risk assessment at the Emergency Limit Condition (ELC) of an important communication axes of the Eixample district of Barcelona The zone is located around Hospital Clinic along the Villarroel Street and it is commonly known as “Antiga Esquerra de l’Eixample” (old left of Eixample). It covers an area of 27,700 mq. The hospital, as the main public healthcare provider in its area of influence, serves a population of 540,000 inhabitants. The Emergency Department is in a 7-floor building, located at the side of Villaroel Street (see Figure 4.14 and Figure 4.15).

Figure 4.14 Aerial view of Hospital Clinic, Antiga Esquerra de l'Eixample, Barcelona.

Figure 4.15 Map of the Hospital Clinic, Barcelona.

According to §2.5, the urbanistic texture of Eixample district has been studied in order to detect the units, which constitute the ELC.

Emergency connection routes:

- Villarroel Street (width 20 m).
- Aragon Street (width 30m).

Aragon street has been chosen because it is wide enough to allow the circulation in case of emergency scenarios. In this street it is also located the fire department.

Figure 4.16 shows the aforementioned emergency routes on a GIS map.

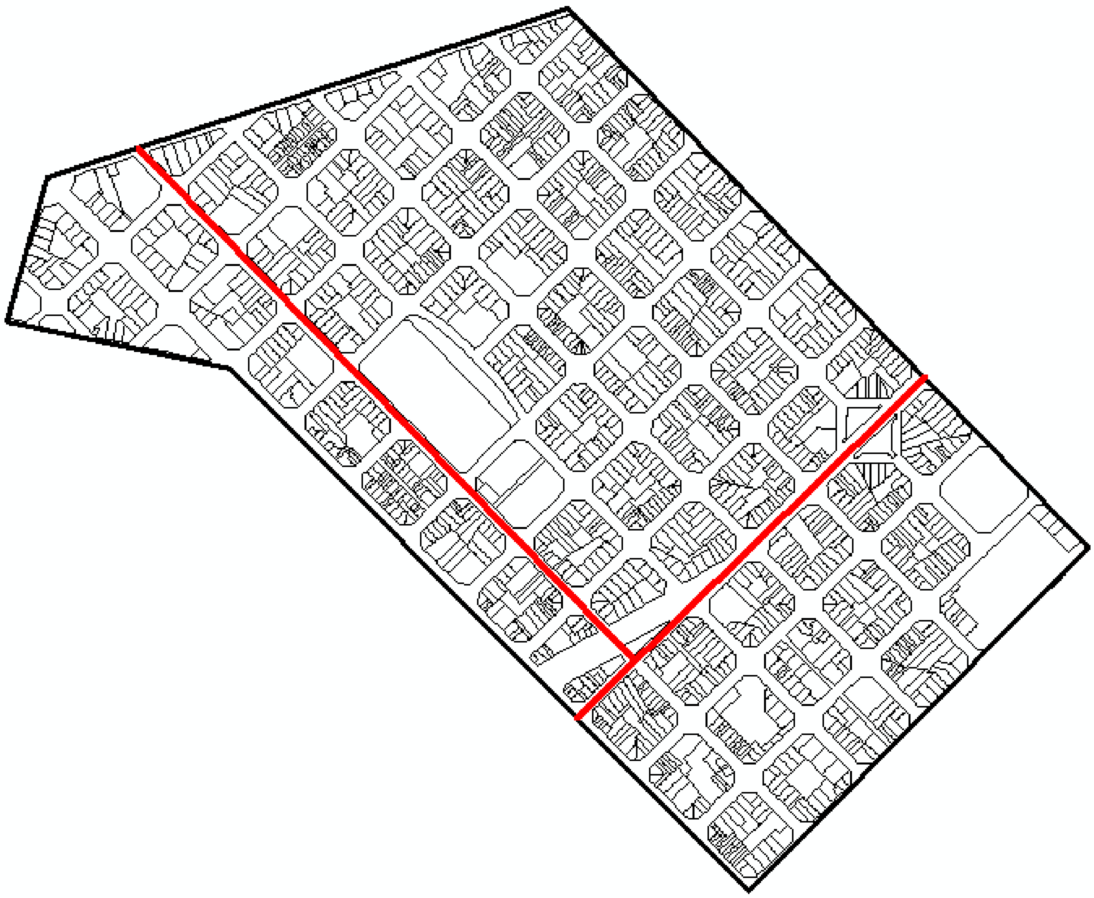


Figure 4.16 Map view on GIS of the Emergency Routes of the Antiga Esquerra de l'Eixample neighborhood.

Emergency area:

- Plaza Letamendi

- Plaza Gall
- Plaza Jardins de Marcos Redondo
- Park of University of Barcelona

Figure 4.17 shows the emergency areas on the GIS map.

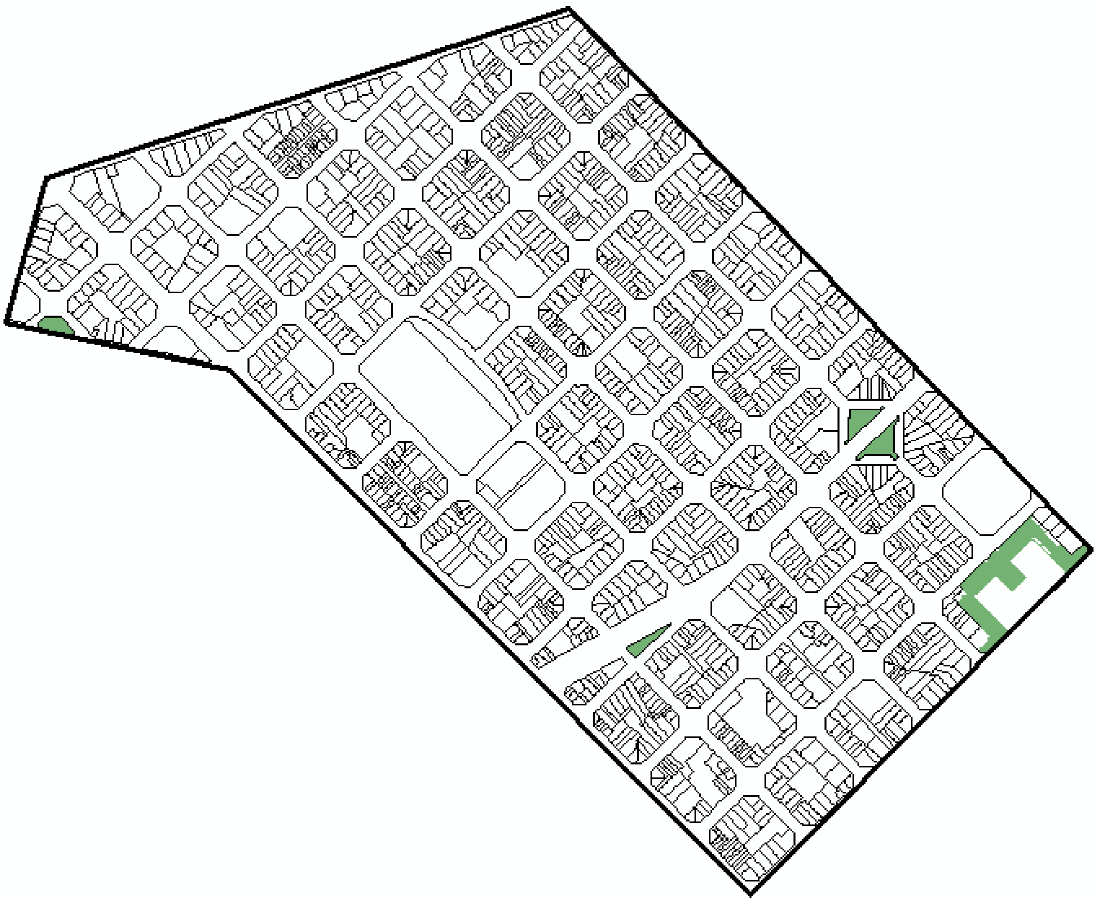


Figure 4.17 Map view on GIS of Emergency Areas of the Antiga Esquerra de l'Eixample neighborhood.

Strategic buildings:

The strategic buildings of the analyzed neighborhood close to Hospital Clinic according to ELC guidelines are the Hospital Clinic and the Primary Attention Center (see Table 4.2). Figure 4.18 shows the strategic buildings on the GIS map.

Table 4.2 Strategic buildings of the analyzed neighborhood close to Hospital Clinic: ubication, number of floors, year of construction and typology (M: masonry, RC: Reinforced Concrete).

STRATEGIC BUILDINGS				
NAME	STREET	N°	YEAR	TYPE
HOSPITAL CLINIC	VILLARROEL	170	1909	M
CENTRE D'ATENCIO' PRIMARIA	ROSSELLON	161	1995	RC

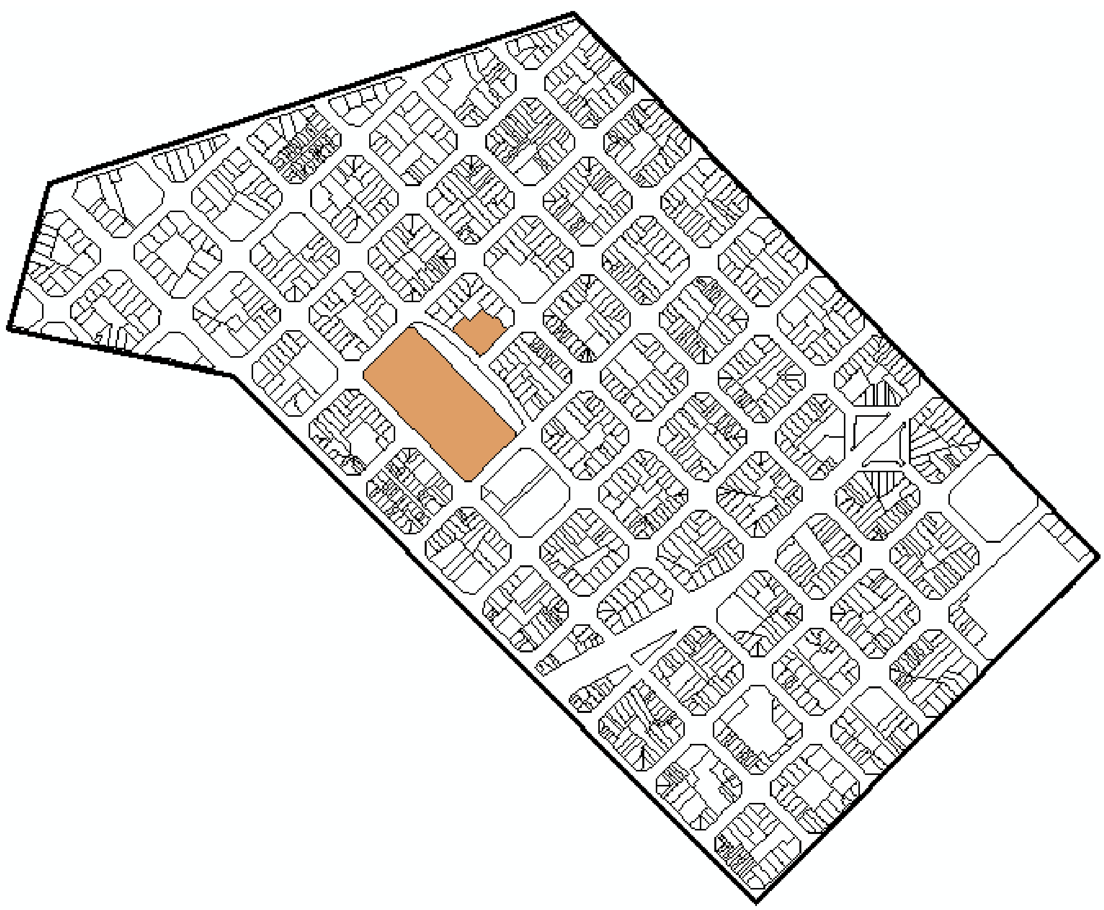


Figure 4.18 Map view on GIS of Strategic Buildings of the Antiga Esquerra de l'Eixample neighborhood.

Interfering buildings:

The list of interfering buildings is shown in Table 4.3 and the representation of them in GIS map is shown in Figure 4.19.

Table 4.3 Interfering buildings of Villarroel Street: ubication, number of floors, year of construction and typology (M: masonry, RC: Reinforced Concrete).

VILLARROEL STREET				
#	N°	N° OF FLOORS	YEAR	TYPE
1	114-122	8	1965	RC
2	117-119	8	1977	RC
3	121	8	1960	RC
4	123	8	1960	RC
5	127	8	1962	M
6	126-128	8	1940	M
7	130-132	8	1965	RC
8	133-135	8	1965	RC
9	137-139	8	1965	RC
10	134	8	1950	M
11	138	8	1975	RC
12	140	8	1951	M
13	141	8	1976	RC
14	162-164	8	1960	RC
15	165	8	1967	RC
16	167	8	1976	RC

17	171	8	1975	RC
18	172-174	8	1978	RC
19	175	8	1981	RC
20	177-179	8	1981	RC
21	181	8	1969	RC
22	184	8	1965	M
23	186	8	1963	M
24	187	8	1968	RC
25	188	8	1949	RC
26	191	8	1971	RC
27	194-196	8	1980	RC
28	197	8	1965	RC
29	200	8	1964	RC
30	205-219	8	1970	RC
31	204-206	8	1967	RC
32	208-214	8	1967	RC
33	220-222	8	1963	RC
34	224-226	8	1963	RC
35	223	8	1981	RC
36	228-236	8	1941	RC
37	231	8	1932	M
38	233	8	1929	M
39	235	8	1951	RC
40	237	8	1951	RC
41	245-249	8	1967	M
42	253	8	1961	RC
43	255	8	1963	M
44	257-261	8	1969	RC

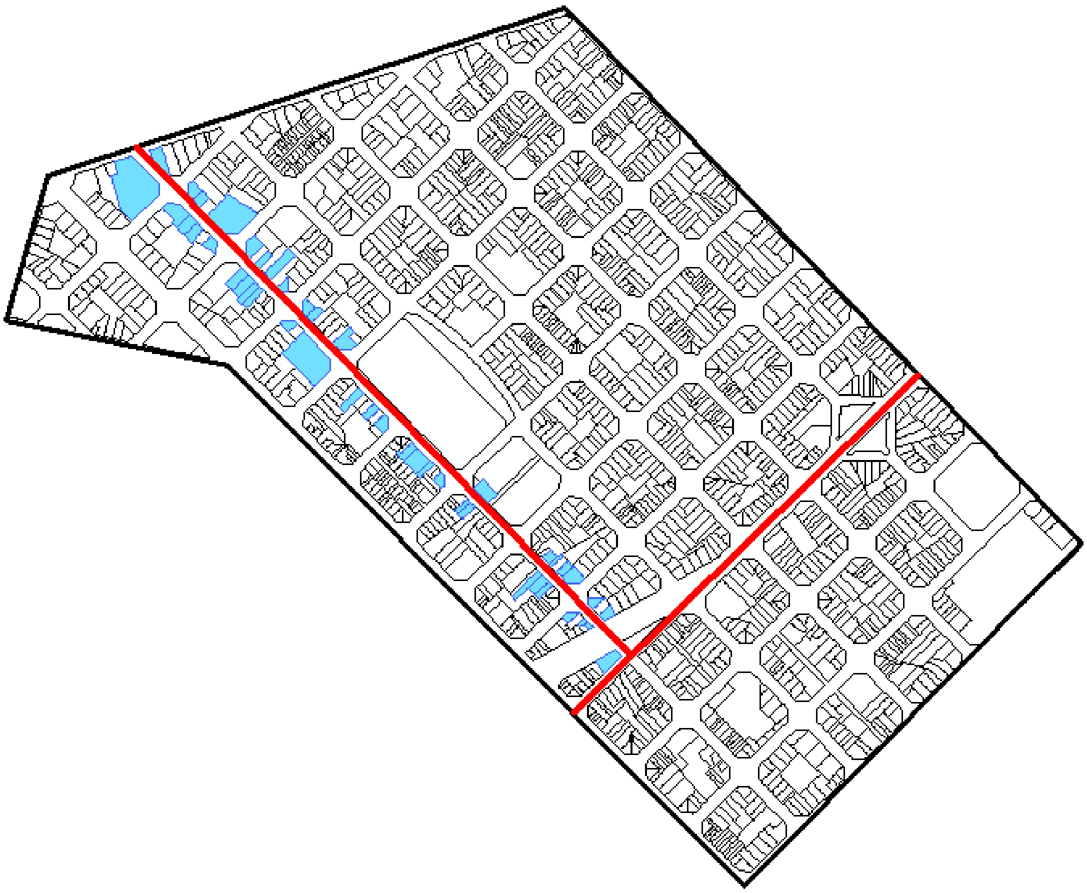


Figure 4.19 Map view on GIS of Interfering Buildings of the Antiga Esquerra de l'Eixample neighborhood.

The ELC analysis of the urban settlement was made using the set of forms provided by the Technical Committee within the O.P.C.M. 3907/2010. In particular 5 different forms are available (source: http://www.protezionecivile.gov.it/resources/cms/documents/IstruzioniSchedeCLE_2_0_open.pdf):

- SB-strategic building (US in ELC manual)
- EA-emergency area (AE in ELC manual)

- AI-accessibility/connection infrastructure (AC in ELC manual)
- SA-structural aggregate (AS in ELC manual)
- SU-structural unit (US in ELC manual)

A representation of all this elements is shown in Figure 4.20.

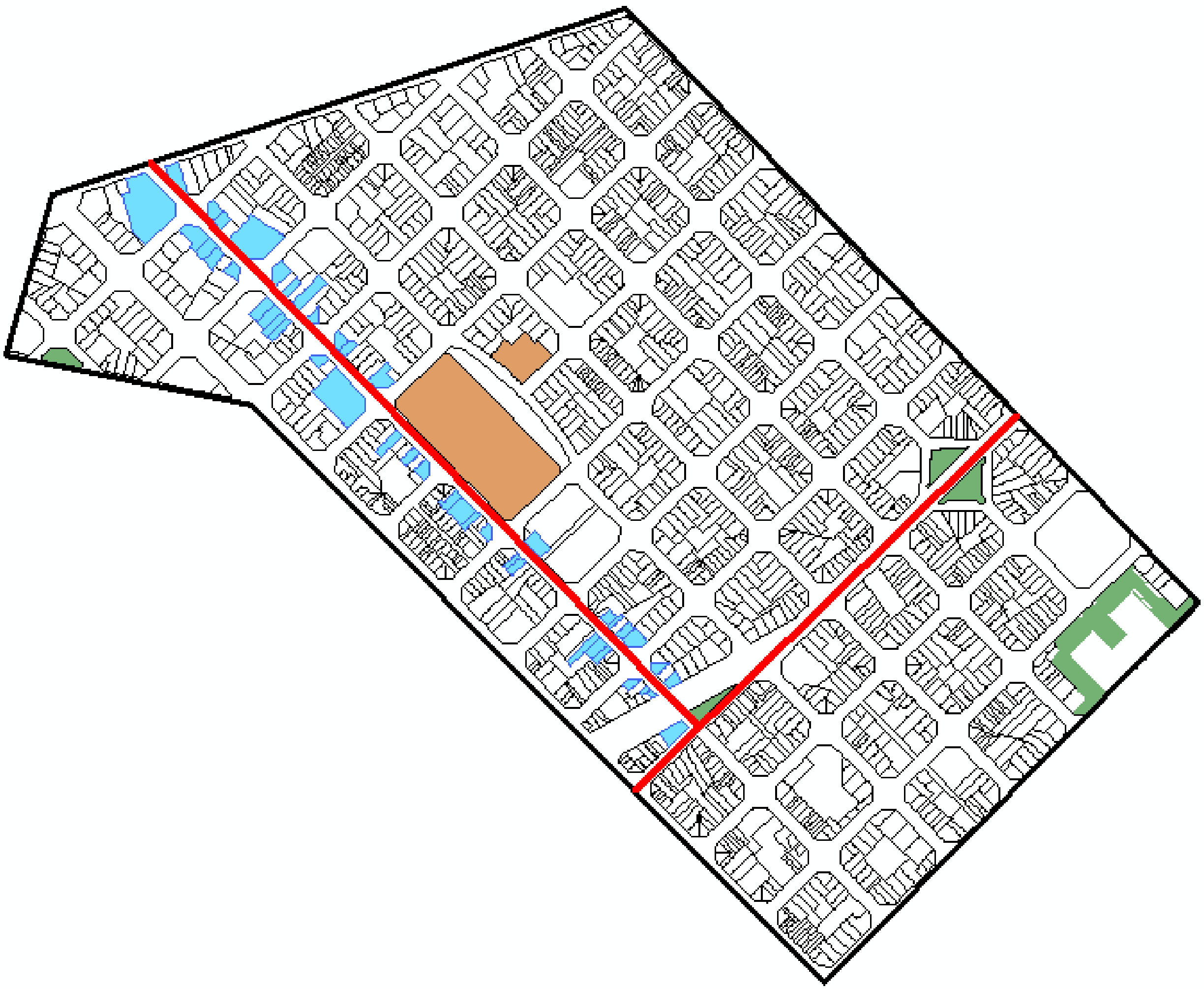


Figure 4.20 Map view on GIS of ELC of the Antiga Esquerra de l'Eixample neighborhood.

4.4.1 Detailed level of post-seismic survey (Level II)

Vulnerability assessment forms are classified by their detail level, i.e. how much information about the building's structure and architecture are needed to completely fill them. Clearly, increasing the detail level, the evaluation is more accurate.

Three levels of knowledge are defined:

- L0, this form only provides the approximate acquisition of building's data and is used for all the structural types with the purpose of gathering them in a comprehensive database with a geographical interface;
- L1, this form includes all information regarding the building's location, geometry and type. It can be used to evaluate exposition and/or vulnerability.
- L2, this form includes all elements involved while assessing the structure's behavior under seismic load. It constitutes the most precise level to be used in the vulnerability assessment.

The vulnerability assessment of Eixample, Barcelona was made with GNDT-II forms (L2).

4.5 ANALYSIS OF RESULTS

The results of the research are shown in the present section. The order of the results is the same of the stages described in Chapter 3.

4.5.1 Data base: Antiga Esquerra de l'Eixample

After different visits in the *Arxiu Contemporani de Barcelona* the data necessary have been obtained. To calculate the vulnerability indexes according to GNDT II detailed information has been needed such as: the floor plans of every building (which in the most of the cases were different from a floor to another) to define the regularity in plan; the sections and the facade to define the regularity in height; a description of constructive typology, materials used, load analysis; information about the foundations, slab floors and the roof and information about the general maintenance conditions. The figures 4.21, 4.22 and 4.23 show an example of information obtained in the archive.

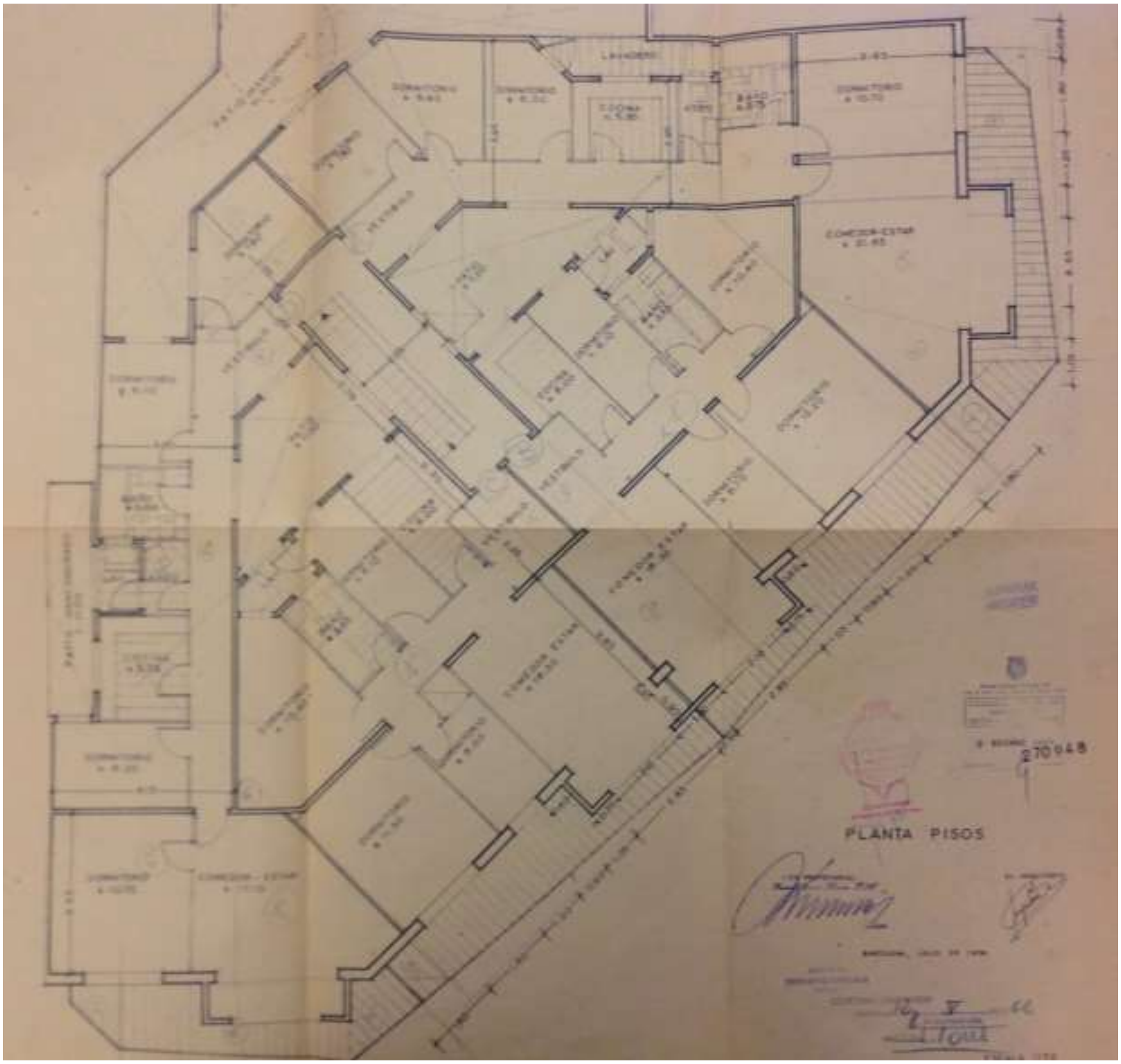
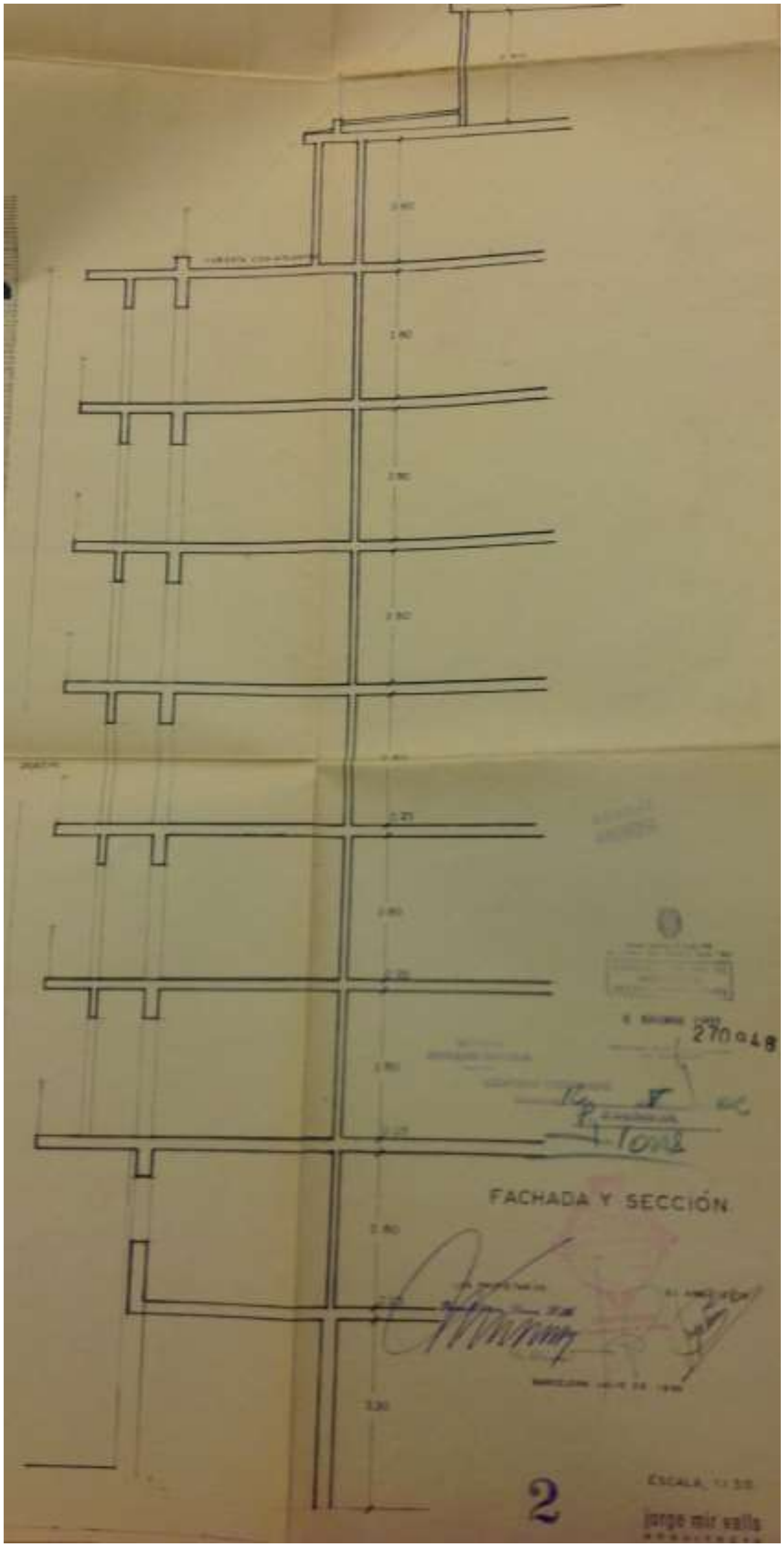
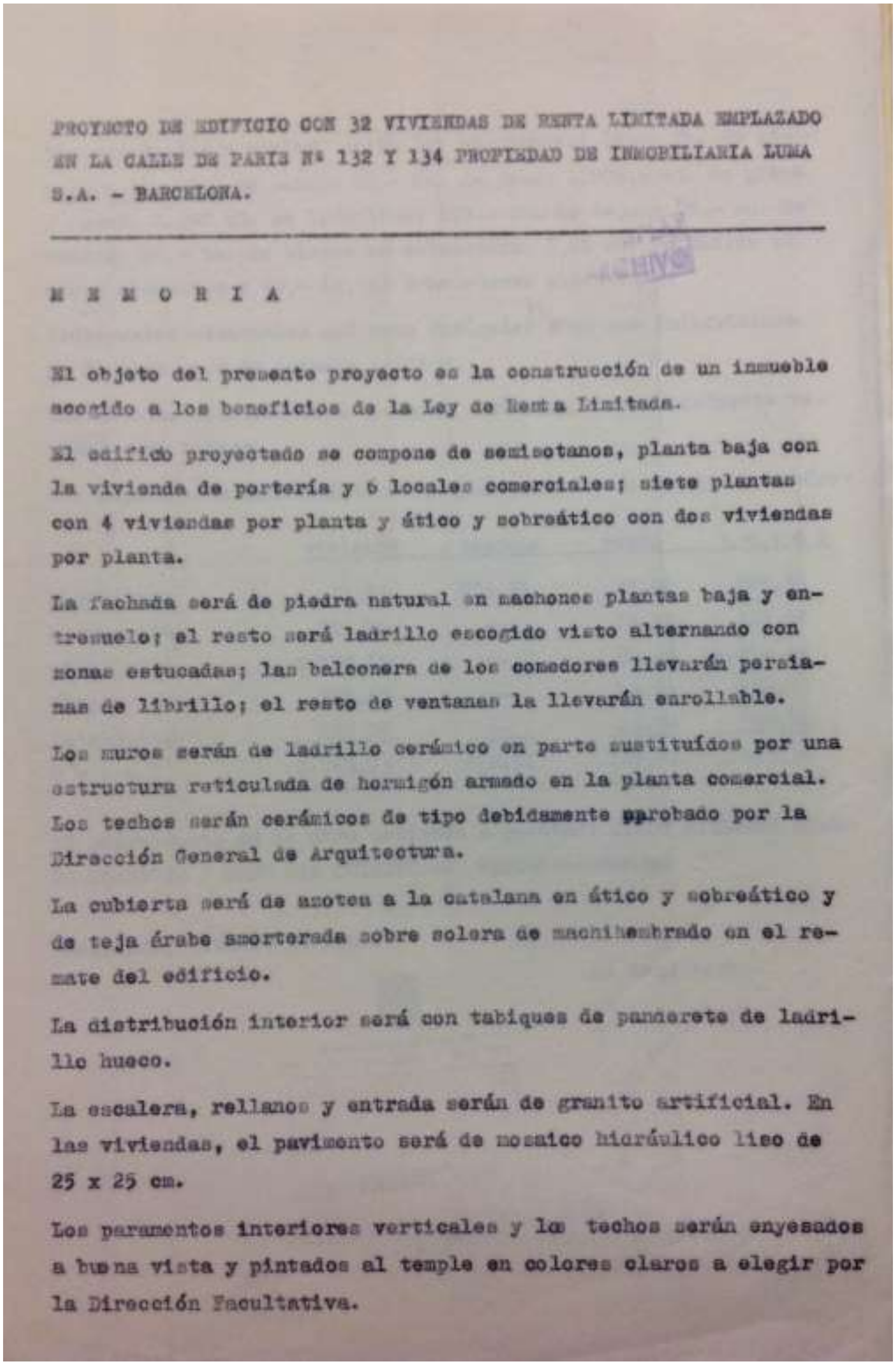


Figure 4.21 Floor plan of Villarroel Street 186.



270048
FACHADA Y SECCIÓN
2
ESCALA 1:50
jorge mir valls

Figure 4.22 Section of Villarroel Street 186.



PROYECTO DE EDIFICIO CON 32 VIVIENDAS DE RENTA LIMITADA EMPLAZADO EN LA CALLE DE PARIS Nº 132 Y 134 PROPIEDAD DE INMOBILIARIA LUMA S.A. - BARCELONA.

M E M O R I A

El objeto del presente proyecto es la construcción de un inmueble acogido a los beneficios de la Ley de Renta Limitada.

El edificio proyectado se compone de semisotanos, planta baja con la vivienda de portería y 6 locales comerciales; siete plantas con 4 viviendas por planta y ático y sobreático con dos viviendas por planta.

La fachada será de piedra natural en machones plantas baja y entresuelo; el resto será ladrillo escogido visto alternando con zonas estucadas; las balconera de los comedores llevarán persianas de librillo; el resto de ventanas la llevarán enrollable.

Los muros serán de ladrillo cerámico en parte sustituídos por una estructura reticulada de hormigón armado en la planta comercial. Los techos serán cerámicos de tipo debidamente aprobado por la Dirección General de Arquitectura.

La cubierta será de azotea a la catalana en ático y sobreático y de teja árabe amorterada sobre solera de machihembrado en el remate del edificio.

La distribución interior será con tabiques de panderete de ladrillo hueco.

La escalera, rellanos y entrada serán de granito artificial. En las viviendas, el pavimento será de mosaico hidráulico liso de 25 x 25 cm.

Los paramentos interiores verticales y los techos serán enyesados a buena vista y pintados al temple en colores claros a elegir por la Dirección Facultativa.

Figure 4.23 Description form of Villarroel Street 186.

4.5.2 Vulnerability indexes

All GNDT-II filled forms for the CLE sub-system of District of Barcelona are attached to Annex B, C, D. In the paragraphs below a summary of vulnerability indexes for different structural types is presented.

Vulnerability forms for masonry buildings were filled following the GNDT-II handbook's instructions provided by the Regione Toscana website (see: http://www.regione.toscana.it/documents/10180/12262198/vsm_man.pdf/095d3648-191d-43aa-ae88-ad78cff79fb3). Table 4.4 shows the vulnerability index of masonry buildings of Villarroel Street.

Table 4.4 Vulnerability index of masonry buildings in two directions according to GNDT form (ubication, vulnerability index in direction x and y).

Villarroel Street		
N°	I_X	I_Y
126-128	56.84	56.84
127	46.58	56.84
134	56.84	56.84
140	53.42	53.42
184	60.26	60.26
186	56.84	56.84
231	56.84	46.58
233	63.89	63.89
245-249	56.84	56.84
255	53.42	53.42

Considering the masonry buildings as aggregates (see Section 2.6.2) and applying the proposal of Basaglia (Basaglia 2015) the updated vulnerability index has been obtained. The new values are shown in Table 4.5.

Table 4.5 Vulnerability index of masonry buildings in two directions considered as aggregates (ubication, vulnerability index in direction x and y).

Villarroel Street		
N°	I_X	I_Y
126-128	47.86	47.86
127	51.50	51.50
134	57.30	58.54
140	46.15	46.15
184	49.57	49.57
186	52.35	52.35
231	49.36	44.23
233	48.15	48.15
245-249	56.84	56.84
255	50.64	50.64

For R.C buildings the vulnerability forms were filled following the GNDT-II handbook's instructions provided by the Regione Marche website (see: rischiosismico.regione.marche.it/Portals/0/RISCHIOSISMICO/MANUALI/05---manuale2ca.pdf). Table 4.6 shows the vulnerability index of reinforced concrete buildings of Villarroel Street.

Table 4.6 Vulnerability index of RC buildings in two directions according to GNDT form (ubication, vulnerability index in direction x and y).

Villarroel Street		
N°	I_X	I_Y
114-122	50.35	50.35
117-119	45.4	45.1
121	52.9	52.9
123	52.9	52.9
130-132	50.35	50.35
133-135	45	45
137-139	27.7	27.7
138	32.7	32.7
141	30.21	30.21
162-164	45.3	45.3
165	50.35	50.35
167	50.35	50.35
171	35.3	35.3
172-174	47.8	47.8
175	45.3	45.3
177-179	45.3	45.3
181	45.3	45.3
187	50.35	50.35
188	45.4	45.1
191	50.35	50.35
194-196	45.4	45.1
197	37.8	32.7
200	42.8	42.8
205-219	27.7	27.7
204-206	60	60
208-214	50.35	50.35
220-222	65	62.5
224-226	50.35	50.35
223	27.7	27.7
228-236	45.4	45.1
235	50.35	50.35
237	50.35	50.35
253	35.2	35.2
257-261	45.4	45.1

After defining the vulnerability indexes in the two principal directions, the total vulnerability index for seismic action angle from 0° to 360° has been calculated. It has been noticed that for 90º angle the value of vulnerability index is higher. Table 4.7 represents the vulnerability index according to a seismic action perpendicular to the buildings being it the worst case.

Table 4.7 Vulnerability index in 90º angle with respect to East.

Villarroel Street	
N°	Iα
114-122	71.11
117-119	63.92
121	74.66
123	74.66
127	72.73
126-128	67.60
130-132	71.11
133-135	63.55
137-139	39.11
134	81.76
138	46.22
140	65.18
141	42.66
162-164	64.00
165	71.11
167	71.11
171	49.78
172-174	67.55
175	64.00
177-179	64.00
181	64.00

184	70.01
186	73.93
187	71.11
188	63.92
191	71.11
194-196	63.92
197	49.96
200	60.44
205-219	39.11
204-206	84.74
208-214	71.11
220-222	90.13
224-226	71.11
223	39.11
228-236	63.92
231	66.28
233	68.00
235	71.11
237	71.11
245-249	80.27
253	49.78
255	71.52
257-261	63.92

4.5.3 Damage grade

After defining the vulnerability indexes for each building, the vulnerability using the Equation 3.12 for masonry buildings and the Equation 3.13 for reinforced buildings. Table 4.8 shows the vulnerability of buildings of Villarroel Street.

Table 4.8 Vulnerability of buildings of Villarroel Street.

Villarroel Street	
N°	V
114-122	1.07
117-119	1.01
121	1.10
123	1.10
127	1.01
126-128	0.98
130-132	1.07
133-135	1.01
137-139	0.76
134	1.06
138	0.84
140	0.96
141	0.80
162-164	1.01
165	1.07
167	1.07
171	0.87
172-174	1.04
175	1.01
177-179	1.01
181	1.01

184	0.99
186	1.01
187	1.07
188	1.01
191	1.07
194-196	1.01
197	0.87
200	0.98
205-219	0.76
204-206	1.19
208-214	1.07
220-222	1.23
224-226	1.07
223	0.76
228-236	1.01
231	0.97
233	0.98
235	1.07
237	1.07
245-249	1.05
253	0.87
255	1.00
257-261	1.01

Using the Equation 3.4 and having defined before the vulnerability for each building, the damage grade has been calculated. Table 4.9 shows the values of damage grade for intensities scale from 5 to 12.

Table 4.9 Damage grade for intensities scale from 5 to 12 of Villarroel Street.

Damage grade μ_D								
N°\I	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00
114-122	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
117-119	0.44	1.27	3.10	3.97	4.60	5.00	5.00	5.00
121	0.57	1.56	3.64	4.38	4.87	5.00	5.00	5.00
123	0.57	1.56	3.64	4.38	4.87	5.00	5.00	5.00
127	0.43	1.27	3.08	3.96	4.59	5.00	5.00	5.00
126-128	0.39	1.18	2.91	3.81	4.50	4.94	5.00	5.00
130-132	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
133-135	0.43	1.26	3.08	3.95	4.59	5.00	5.00	5.00
137-139	0.11	0.54	1.58	2.55	3.51	4.28	4.80	5.00
134	0.51	1.42	3.39	4.19	4.75	5.00	5.00	5.00
138	0.20	0.74	2.02	3.02	3.90	4.56	4.98	5.00
140	0.37	1.13	2.82	3.74	4.45	4.91	5.00	5.00
141	0.16	0.64	1.80	2.79	3.71	4.43	4.90	5.00
162-164	0.44	1.28	3.10	3.97	4.61	5.00	5.00	5.36
165	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
167	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
171	0.25	0.85	2.25	3.23	4.07	4.67	5.00	5.00
172-174	0.48	1.37	3.30	4.12	4.70	5.00	5.00	5.00
175	0.44	1.28	3.10	3.97	4.61	5.00	5.00	5.00
177-179	0.44	1.28	3.10	3.97	4.61	5.00	5.00	5.00
181	0.44	1.28	3.10	3.97	4.61	5.00	5.00	5.00
184	0.41	1.22	2.99	3.88	4.54	4.97	5.00	5.00
186	0.44	1.29	3.12	3.99	4.62	5.00	5.00	5.00
187	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
188	0.44	1.27	3.10	3.97	4.60	5.00	5.00	5.00
191	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
194-196	0.44	1.27	3.10	3.97	4.60	5.00	5.00	5.00
197	0.25	0.86	2.26	3.25	4.08	4.68	5.00	5.00
200	0.39	1.17	2.90	3.81	4.49	4.94	5.00	5.00

205-219	0.11	0.54	1.58	2.55	3.51	4.28	4.80	5.00
204-206	0.68	1.77	4.05	4.66	5.04	5.00	5.00	5.00
208-214	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
220-222	0.73	1.86	4.23	4.78	5.10	5.00	5.00	5.00
224-226	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
223	0.11	0.54	1.58	2.55	3.51	4.28	4.80	5.00
228-236	0.44	1.27	3.10	3.97	4.60	5.00	5.00	5.00
231	0.38	1.15	2.86	3.77	4.47	4.92	5.00	5.00
233	0.40	1.18	2.92	3.82	4.50	4.94	5.00	5.00
235	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
237	0.53	1.47	3.48	4.26	4.79	5.00	5.00	5.00
245-249	0.49	1.40	3.34	4.15	4.72	5.00	5.00	5.00
253	0.25	0.85	2.25	3.23	4.07	4.67	5.00	5.00
255	0.42	1.24	3.04	3.92	4.57	4.98	5.00	5.00
257-261	0.44	1.27	3.10	3.97	4.60	5.00	5.00	5.00

4.5.4 Fragility curves

The present section shows the fragility curves for masonry and reinforced concrete buildings of Villarroel Street. Since the number of buildings examined is high, herein it is presented only the minimum, maximum and mean values of the vulnerability indexes, respectively for masonry and R.C. buildings. So, to have a concise but comprehensive view, the trend of fragility curves is displayed for these values. Figure 4.24 shows the fragility curves for masonry buildings for minimum, mean and maximum value of vulnerability index respectively. Figure 4.25 shows the fragility curves for RC buildings for minimum, mean and maximum value of vulnerability index respectively.

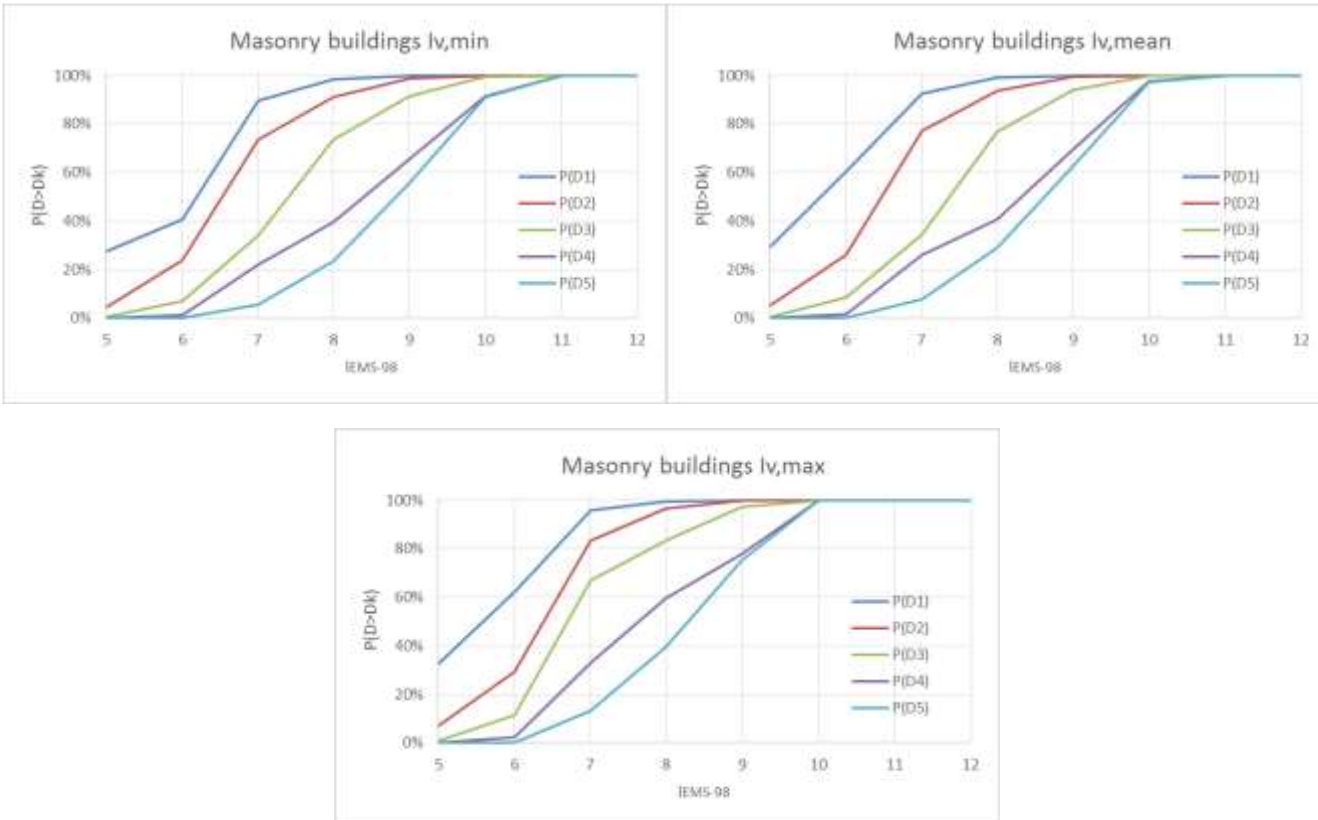


Figure 4.24 Fragility curves for masonry buildings for minimum, mean and maximum value of vulnerability index.

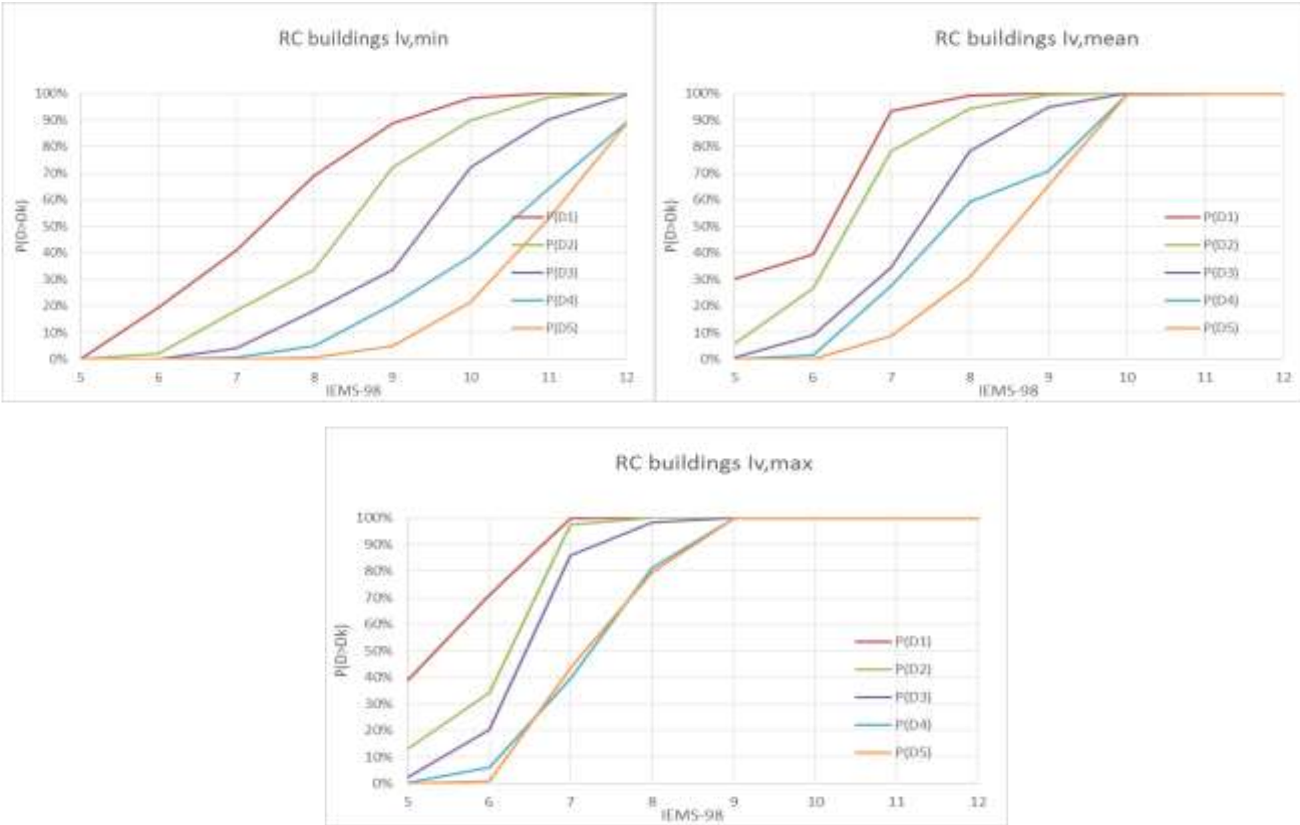


Figure 4.25 Fragility curves for RC buildings for minimum, mean and maximum value of vulnerability index.

4.5.5 Loss assessment

Using the Equations 3.22, 3.23, 3.24 and 3.25, combined probabilities and counts of collapsed or unusable buildings after the seismic event are displayed in Figure 4.26.

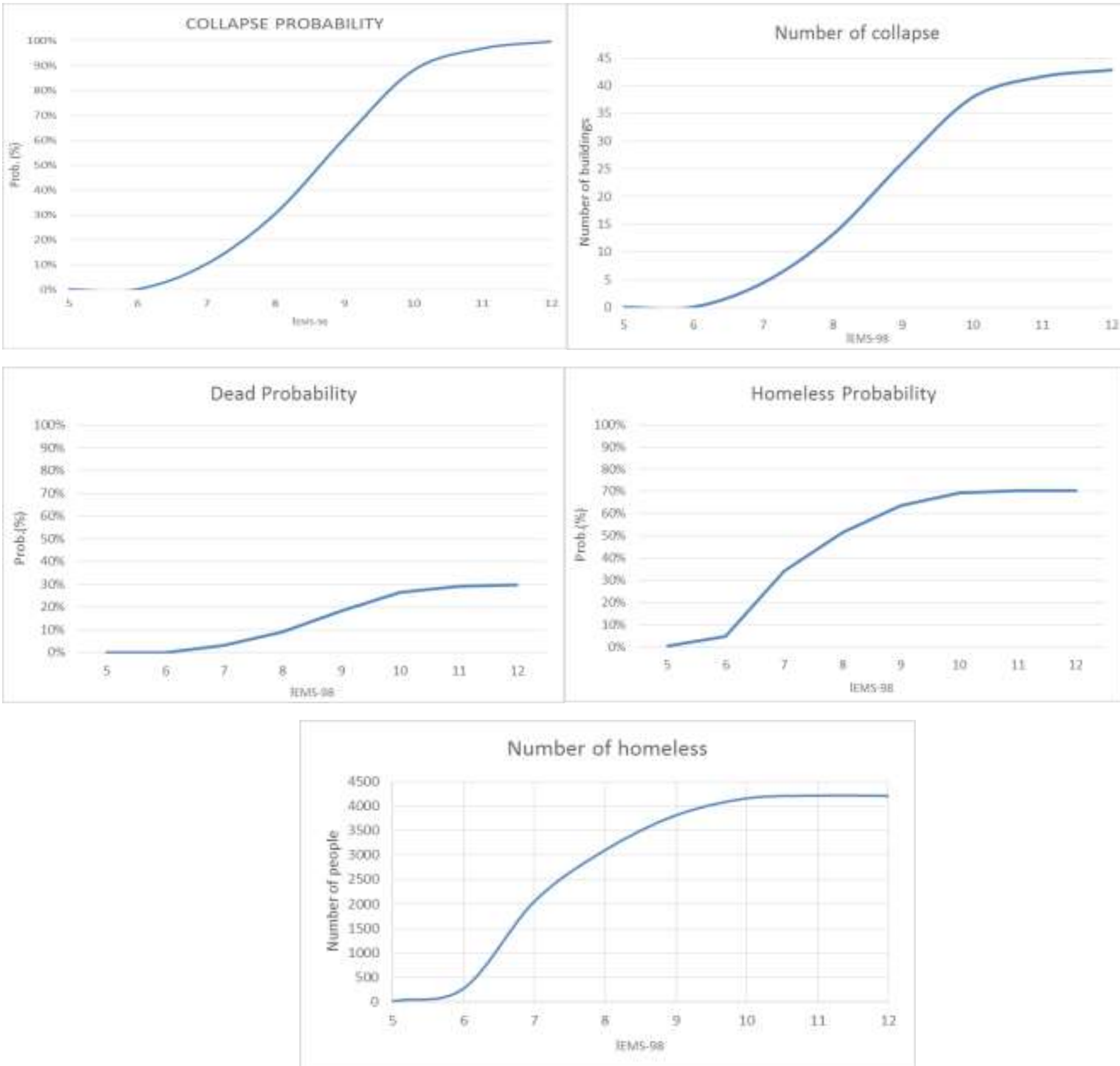


Figure 4.26 Different probability curves (Collapse probability, Number of Collapse, Dead probability, Homeless probability, Number of homeless).

4.5.6 Seismic Scenario: GIS

After calculating all the previous data in Excel, the GIS software has been used to display the visual maps of the Antigua Esquerra de l'Eixample in order to provide a quick overview of the earthquake effects for a specific direction and/or increasing intensities. The values have been organized using different sheets for every seismic intensity. The Excel-GIS association has been made through the FID (building's ID). Figure 4.27 shows the mean vulnerability index for CLE buildings of Villarroel Street.

Figure 4.27 Vulnerability index map of Villarroel Street for CLE sub-system.

Figures 4.28, 4.29, 4.30 and 4.31 show the map of the neighborhood with the definition of the damage grade in the buildings for increasing intensities in the range I=6-9. In this way, it is possible to display effectively the increasing impact of the earthquake on the buildings.

Figure 4.28 Mean damage grade (I=6) map of Villarroel Street for CLE sub-system.

Figure 4.29 Mean damage grade (I=7) map of Villarroel Street for CLE sub-system.

Figure 4.30 Mean damage grade (I=8) map of Villarroel Street for CLE sub-system.

Figure 4.31 Mean damage grade (I=9) map of Villarroel Street for CLE sub-system.

Chapter 5

CONCLUSIONS

5.1 SUMMARY

The assessment of the city centres has become an important topic in the national urban planning. After decades of public policies promoting new construction, the rehabilitation of urban centers has become now a priority for different countries.

This research deals with the assessment of the seismic vulnerability at the urban scale. An important contribution of the thesis is the identification and organization of strategies and methodologies related to the process of urban rehabilitation. To attend this objective, the study has been related to collection of data in order to improve the level of knowledge of the buildings to identify their constructive typology.

An important component of this dissertation is the assessment of methodologies for the evaluation of the vulnerability risk, the estimation of damage and losses in order to give a contribution to risk prevention strategies.

This study may contribute to the field of investigation strategies and in specific related to the study of seismic vulnerability in an urban scale. In this work was described the difficulties, the challenges, reflection and tendencies of urban rehabilitation. A neighborhood of Eixample was chosen considering the promotional, cultural and strategic value for the city of Barcelona.

5.2 CONCLUDING REMARKS

5.2.1 Analysis of the urban rehabilitation process

The Emergency Limit Condition (ELC) of an urban sub-system has been defined in the research. The study has been limited on the neighborhood of the Antiga Esquerra de l'Eixample of Barcelona. This has permitted to clarify the opportunities of the application of the ELC to urban settlements and also its limitations in the analysis of urban limit conditions.

5.2.2 Definition of the area of study and data collection

Detailed information was necessary in order to apply a second level method of assessment of the seismic vulnerability. The detected ELC sub-system consisted in 43 interfering buildings. A visual analysis at the available information in the public Archive of Barcelona was necessary. The data collection was a rather difficult and time-demanding work since it required a coordination with the office of the Archive. The time factor was very important, being the process rather demanding as for the research of all the useful data, the acquisition of the information, the organization, and the subsequent digitalization.

In addition, there were some uncertainties in the collected data of the buildings. Some information did not exist at all and thus several engineering assumptions were considered in order to interpret correctly the collected information. The plans and technical reports were interpreted from the engineering point of view and the design decisions made in other epochs were analyzed in-depth. Materials' characteristics were carefully evaluated on the basis of available historical documents and standards. The history of each building was reconstructed and in some cases, when the information was missing, it was adapted to that of similar constructive typology. In some documents found in the archive, the analysis of the loads applied to the buildings that was considered at the epoch of the construction were considered not valid today in relation with the current construction performances. In these cases, a new analysis of the applied load was necessary.

5.2.3 Methodology choose

All the different methodologies of seismic vulnerability assessment presented in Chapter 2 are mainly based on the type information required by the analysis. The uncertain range of vulnerability is related to the type and quality of the available information. The methodologies are also conditioned by the scale of application. The objective of this research was to evaluate the seismic vulnerability at the urban scale. A method easy to implement at a large scale, with limited utilization of resources and rather easy to construct seismic scenarios and evaluations of losses should be used. The methodology proposed was that known as GNDT II that is based on the concept of vulnerability index.

5.2.4 Evaluation of the method

After collecting all the helpful data, GNDT forms for masonry and RC buildings were completed. GNDT II method has the purpose of defining the vulnerability of buildings easily but with an acceptable level of precision from the engineering point of view.

The parameter 3 used for the evaluation of the vulnerability index according to the GNDT-II method was divided into the two different directions of the building X and Y, because the conventional strengths could be different along the two directions. However, only in some cases the vulnerability indexes were remarkably different in the two directions. The aggregate effect was also analyzed in this study although the original GNDT II method do not consider this crucial aspect.

The outcomes from the application of the GNDT-II method to a neighborhood of the Eixample district could not be compared with observed data since no important earthquakes have struck the city recently. However, the proposed methodology is based on vast available literature on masonry and RC buildings of the Italian building stock. For this reason, it could be considered as a promising point of departure.

Limited research was found in the existing literature about RC buildings. The correlation between the index of vulnerability Iv and the vulnerability V proposed by Basaglia was considered as a first proposal.

This study verified that although a region has a moderate seismicity, as this is the case of Barcelona, the expected damage level can be high, as the seismic vulnerability is high. The evaluation of the damage level resulted rather high for intensities VII, VIII and IX, revealing that the seismic vulnerability of the buildings of Antiga Esquerra de l'Eixample is rather high.

5.2.5 GIS Software

The use of GIS associated of databases of the buildings was crucial for the evaluation of vulnerability, as well as for displaying easily the results. The GIS can be used as a software for the sensitivity analysis, i.e. many post-earthquake scenarios can be plotted and thus many possible maps of expected damage can be analyzed. The GIS software allowed the evaluation of several seismic scenarios of damage for different seismic intensities. This is very useful in order to have the possibility of rapidly analyzing the buildings pertaining to the urban centre.

5.3 SUGGESTIONS FOR FUTURE WORK

After the evaluation of the seismic risk scenarios, the emergency management system should request interventions of different nature, both on buildings and on the connection infrastructure. The feasibility of the interventions, after going beyond the logic of single buildings' intervention, is favorable to organize an organic planning process. More subjects should be involved to define a major range of resources (economic, social). In this case, a more rapid realization of the interventions can be obtained in an optimal time.

It is not sufficient only to individuate the interventions, but also to incorporate them in the local or regional development plans in order to ensure the adequate resilience and post-earthquake recovery. Regional and national policies can be very important to encourage a deeper study of the seismic vulnerability and evaluation of losses.

The in-depth analysis is suggested of the evaluation method of ELC according to the dimensions of the urban settlements considered. The identification of the ELC sub-system is not univocal. Another ELC sub-system can be proposed in order to do a comparison and choose the most optimal one for the objectives of the study.

In the case of the study of the Antiga Esquerra de l'Eixample, only the ELC sub-system was studied. Future researches may investigate also other limit conditions, such as the Live-saving Limit Condition (LLC), Damage Limit Condition (DLC), etc.

The data collection is rather time-demanding process. It could be possible the creation of groups of voluntaries in order to research massive quantities of data to extend the study form a neighborhood to the whole district and then to the whole city. In this way, the citizens could be aware of their central role in the society as for the establishment of public well-being and safety.

Even if a certain level of error is considered acceptable for such large scale analysis, more revisions of the method are necessary to ensure the accepted level of precision. In particular, it should be necessary to redefine the weight of the "Conventional Strength" parameter for masonry buildings, giving a higher influence to the change of the earthquake direction. In addition, the "parameter five" related to the direction of the floor plan could be also separated for different earthquake directions. In case of the buildings of the Eixample district, most of them presented and unidirectional behavior so the vulnerability index in two direction could be different.

The correlation between I_v and V for RC buildings could be improved by future works, in analogy with the one for masonry buildings.

Future researches could include also all other elements that form a settlement. Some preliminary studies of this kind have already been done. In particular:

- Steel buildings, see the form released by the NDMA (National Disaster Management Authority, India, source:

http://www.ndma.gov.in/images/disaster/earthquake/10b%20Steel _Survey_Form.pdf) or the work by Bermúdez (Bermúdez et al. 2008)

- Timber structures, see Parisi (Parisi et al. 2008)
- Dams, whose breakage would have dramatic effects on cities with an average elevation below or really close to the sea level. The consequent flooding indeed would not only cause additional damages but also severely slow down all the emergency procedures ((Tosun et al. 2006))
- Pipelines, see Manshoori (Manshoori 2011)
- Connection routes, (D'Andrea et al. 2005)
- Bridges, as their breakage or just temporary interruption of usage could prevent the access to the city of rescue vehicles (ambulances and fire trucks) as well as the inhabitants' evacuation from it. See Lazzali (Lazzali & Farsi 2009)

Finally, it must be noticed that this study has considered only the specific aspect of the seismic hazard. However, policies aimed at the improvement of the resiliency of urban centres should also consider other types of natural hazards (floods, tsunamis, landslides, etc.), as well as anthropic ones (terrorism attacks, explosions in power plants, etc.).

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https://www.usgs.gov/

ANNEX A: GNDT II ORIGINAL FORMS

G.N.D.T. - SCHEDA DI VULNERABILITÀ DI 2° LIVELLO (MURATURA)

Cod. ISTAT Provincia [1]	Cod. ISTAT Comune [3]	Scheda n° [6]

	PARAMETRI	Classi	Qualità inform.	ELEMENTI DI VALUTAZIONE	
1	TIPO ED ORGANIZZAZIONE DEL SISTEMA RESISTENTE (S.R.)	11	22	Norm. nuove costruzioni (cl. A)	33 1
				Norm. riparazioni (cl. A)	2
				Cord. e cat. a tutti i livelli (cl. B)	3
				Buoni ammor. tra murat. (cl. C)	4
				Senza cord. cattivi ammor. (cl. D)	5
2	QUALITÀ DEL S.R.	12	23	(vedi manuale)	34
3	RESISTENZA CONVENZIONALE	13	24	Numero di piani **N**	35
				Area tot. cop. A_t (mq)	37
				Area A_x (mq)	41
				Area A_y (mq)	44
				τ_k (t/mq)	47
				Alt. media interp. **h** (m)	50
				Peso spec. par. p_m (t/mc)	52
				Carico perm. sol. p_s (t/mq)	54
4	POSIZIONE EDIFICIO E FONDAZIONI	14	25	Pendenza perc. terreno	56
				Roccia	fond. si 58 1 no 2
				Terreno sc. non sping.	fond. si 3 no 4
				Terreno sc. sping.	fond. si 5 no 6
				Diff. max di quota Δh (m)	59
5	ORIZZONTAMENTI	15	26	Piani sfalsati	62 si 1 no 2
				Orizz. rig. e ben coll.	63 1
				Orizz. def. e ben coll.	2
				Orizz. rig. e mal coll.	3
				Orizz. def. e mal coll.	4
				% orizz. rig. ben coll.	64
6	CONFIGURAZIONE PLANIMETRICA	16	27	Rapp. perc. $\beta_1 = a / l$	66
				Rapp. perc. $\beta_2 = b / l$	70
7	CONFIGURAZIONE IN ELEVAZIONE	17	28	Rapp. % ΔM / M (+) aumento (-) riduzione	74
				Rapp. perc. T / H	77
				Perc. in sup. port.	79
				Piano terra port.	81 si 1 no 2
8	D_{max} MURATURE	18	29	Rapp. massimo **l / s**	82
9	COPERTURA	19	30	Cop. non sp. 84 0 poco sp. 1 sp. 2	
				Cordoli in copertura	85 si 1 no 2
				Catene in copertura	86 si 1 no 2
				Carico perm. cop. p_c (t/mq)	87
				Lungh. app. cop. l_a (m)	90
				Perimetro copertura **l** (m)	93
10	ELEM. NON STRUTT.	20	31	(vedi manuale)	
11	STATO DI FATTO	21	32	(vedi manuale)	

SCHEMI - RICHIAMI (MURATURA)

Parametro 3 - Resistenza convenzionale

Tipologia struttura verticale τ_k (t/mq) ______

Minimo tra A_x e A_y A (mq) ______

Massimo tra A_x e A_y B (mq) ______

Coefficiente $a_0 = A / A_t$ ______

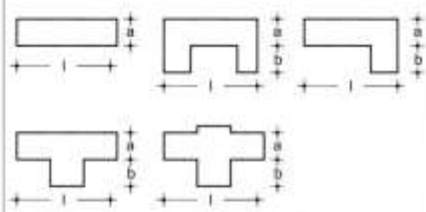
Coefficiente $\gamma = B / A$ ______

$q = (A_x + A_y) \cdot h \cdot \frac{p_m}{A_t} + p_s$ ______

$C = \frac{a_0 \cdot \tau_k}{q \cdot N} \cdot \sqrt{1 + \frac{q \cdot N}{1.5 \cdot a_0 \cdot \tau_k \cdot (1 + \gamma)}}$ ______

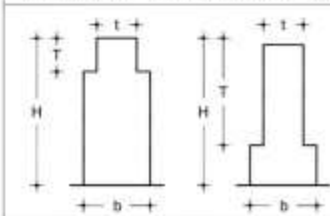
$\alpha = C / 0,4$ ______

Parametro 6 - Configurazione planimetrica



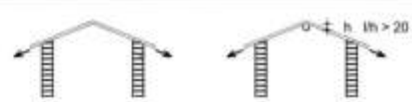
$\beta_1 = \frac{a}{l}$ ______ $\beta_2 = \frac{b}{l}$ ______

Parametro 7 - Configurazione in elevazione



Parametro M8 - D_{max} MURATURE

Parametro M9 - Copertura



Coperture spingenti (tipologia M)

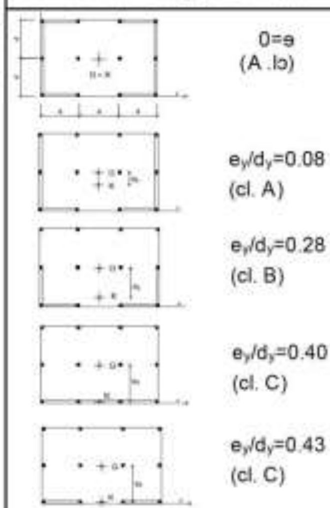
Coperture poco spingenti (tipologia N)

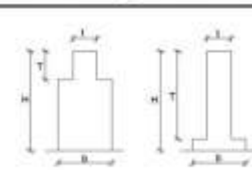
Coperture non spingenti (tipologia O)

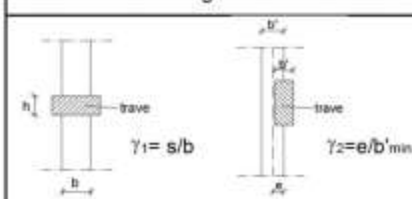
G.D.N.T. - SCHEDA DI VULNERABILITA' DI 2° LIVELLO (CEMENTO ARMATO)

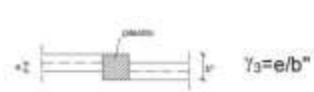
Cod. ISTAT Provincia ☐☐☐ Cod. ISTAT Comune ☐☐☐ N. scheda ☐☐☐☐☐☐ Squadra ☐☐

	PARAMETRI	Classi	Qual. inf.	ELEMENTI DI VALUTAZIONE	SCHEMI - RICHIAMI (CEMENTO ARMATO)
1	TIPO DI ORGANIZZAZIONE DEL SISTEMA RESISTENTE (S.R.)	☐	☐	Pareti in c.a. (cl. A) 1 Tamp. cons. e telai (cl. A) 2 Tamp. deb. e telai rig. (cl. B) 3 Tamp. deb. e telai def. (cl. C) 4 Telai non tamp. (cl. B o C) 5	Parametro 3. Resistenza convenzionale Minimo fra A_x e A_y A ______ Coefficiente $a_0 = A/A_t$ ______
2	QUALITA' DEL S.R.	☐	☐	(vedi manuale) ☐	$q = (A_x+A_y) \cdot h \cdot p_m / A_t + p_s$ ______
3	RESISTENZA CONVENZIONALE	☐	☐	Numero di piani N ☐☐ Area tot. cop. A_t (mq) ☐☐☐☐ Area A_x (mq) ☐☐☐ Area A_y (mq) ☐☐☐ τ_k (t/mq) ☐☐☐ Alt. media interp. h (m) ☐.☐ Peso spec. par. p_m (t.mc) ☐.☐ Carico perm. sol. p_s (t/mq) ☐.☐	$C = a_0 \cdot \tau_k/(q \cdot N)$ ______ $\alpha = C/(0.4 \cdot R)$ ______ Calcolo di R Terreni tipo S_1: R=2.5 (T<0.35 s) $R = 2.5/(T/0.35)^{2/3}$ (T>0.35 s) Terreni tipo S_2: R = 2.2 (T<0.8 s) $R = 2.2/(T/0.8)^{2/3}$ (T>0.8 s) Parametro 6. Configurazione planimetrica
4	POSIZIONE EDIFICIO E FONDAZIONI	☐	☐	Pend. perc. terr. ☐☐ Roccia fond. si 1 no 2 Terr. sc. non sp. si 3 no 4 Terr. sc. sp. si 5 no 6 Diff. Max. di quota Δh (m) ☐.☐	
5	ORIZZONTAMENTI	☐	☐	Piani sfalsati si 1 no 2 Orizz. rig. e ben coll. 1 Orizz. def. e ben coll. 2 Orizz. rig. e mal coll. 3 Orizz. def. e mal coll. 4 % or. rig. ben coll. ☐☐	
6	CONFIGURAZIONE PLANIMETRICA	☐	☐	Rapp. perc. β_1 = a/l ☐☐ Rapp. perc. β_3 = e/d ☐☐ Rapp. perc. β_4 = Δd/d ☐☐ Rapp. perc. β_5 = c/b ☐☐	Parametro 7. Configurazione in elevazione
7	CONFIGURAZIONE IN ELEVAZIONE	☐	☐	% aumento (+) riduz. (-) di massa ☐☐☐ Rapp. perc T/H ☐☐ Var. in elev. s.r. 0 1 1 2 2 Piano terra port. si 1 no 2	
C8	COLLEGAMENTI ED ELEMENTI CRITICI	☐	☐	Rapp. perc. γ_1 = s/b ☐☐ Rapp. perc. γ_2 = e/b'$_{min}$ ☐☐ Rapp. perc. γ_3 = e/b" ☐☐ Rapp. max. h/b_{min} ☐☐ % σ/Rc (approssim.) ☐☐ Colleg. el. pref. si 1 no 2 c.o. 3 Largh. min. b_{min} (cm) ☐☐	Parametro C9. Colleg. ed elementi critici
C9	ELEM. BASSA DUTT.	☐	☐	Rapp. min. h_{min}/b ☐☐ Rapp. max. h_{medio}/h_{min} ☐☐	
10	EL. NON STRUTT.	☐	☐	(vedi manuale)	
11	STATO DI FATTO	☐	☐	(vedi manuale)	
12	Struttura a telai piani o a telai spaziali			piani 1 spaziali 2	









G.D.N.T. - SCHEDA DI VULNERABILITA' DI 2° LIVELLO (CEMENTO ARMATO) - Foglio 2

Note e osservazioni

Eventuale schizzo

ANNEX B: CLE FORMS

ES 1

PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile

CONFERENZA DELLE REGIONI E DELLE PROVINCE AUTONOME

ANALISI DELLA CONDIZIONE LIMITE PER L'EMERGENZA (CLE) DELL'INSEDIAMENTO URBANO

EDIFICIO STRATEGICO
versione 2.0

Sezione 1 - IDENTIFICATIVI

Data compilazione __ / __ / ____ Codice ISTAT

1 Regione
2 Provincia
3 Comune
4 Località abitata
5 Sezione censuaria
6 Identificativo Aggregato Strutturale
7 Identificativo Unità Strutturale
8 Identificativo Area di Emergenza
9 Identificativi infrastrutture di Accessibilità/Connessione a b c d
10 Indirizzo 11 Civico
12b Denominazione 12 Mappa in allegato (vedi retro)

Sezione 2 - CARATTERISTICHE GENERALI

POSIZIONE NELL'AGGREGATO 13 Isolata Si No 14 Interna D'estremità D'angolo
15 FRONTE INTERFERENTE SU INFRASTRUTTURA ACCESSIBILITÀ/CONNESSIONE (H>L) O AREA DI EMERGENZA (H>d) Si No
16 UNITÀ STRUTTURALE SPECIALISTICA Si No 17 Chiesa Teatro Torre/campanile/ciminiera Altro
18 NUMERO PIANI TOTALI (INCLUSI INTERRATI) 19 PIANI INTERRATI 0 1 2 ≥3
20 ALTEZZA MEDIA DI PIANO (m) ≤2,50 2,50-3-50 3,50-5,00 ≥5,00 21 ALTEZZA ALL'IMPOSTA DELLA COPERTURA
22 VOLUME UNICO SU AC Si No 23 SUPERFICIE MEDIA DI PIANO (mq)
24 STRUTTURA PORTANTE VERTICALE C.a. Acciaio Acciaio-c.l.s. Muratura Mista (muratura/c.a.) Legno Non identificata
25 TIPO MURATURA Buona Cattiva Non identificata 26 CORDOLI O CATENE Si No
27 PILASTRI ISOLATI Si No 28 PIANO PILOTIS Si No 29 SOPRAELEVAZIONI Si No
30 DANNO STRUTTURALE Gravissimo Medio - grave Leggero Assente 31 STATO MANUTENTIVO Carente Sufficiente Buono
PROPRIETÀ 32 Pubblica 33 Privata
34 MORFOLOGIA Pianeggiante Su leggero pendio (15°÷30°) Su forte pendio (>30°)
UBICAZIONE 35 Sotto versante incombente o forte pendio 36 Sopra versante incombente o cresta
MICROZONAZIONE SISMICA 37 Zona MS (condizione peggiore) Stabile Stabile con amplificazioni Instabile
Tipo instabilità 38 Frana 39 Liquefazione 40 Faglia attiva e capace 41 Cedimenti differenziali 42 Cavità sotterranee
GEOLOGIA / IDROGEOLOGIA Localizzazione frana 43 Interferente con l'edificio strategico 44 A monte 45 A valle
46 Rischio PAI R1 R2 R3 R4 47 Area alluvionabile Si No

Sezione 3 - CARATTERISTICHE SPECIFICHE

48 IDENTIFICATIVO FUNZIONE STRATEGICA Coordinamento interventi 001 Soccorso sanitario 002 Intervento operativo 003 Altro
49 STRUTTURA DI GESTIONE DELL'EMERGENZA Ccs Dicomac Com Coi Coc 49b Ricovero in emergenza
DESTINAZIONE D'USO 50 Uso originario 51 Uso attuale
52 ANNO DI PROGETTAZIONE 53 ANNO DI FINE COSTRUZIONE
ESPOSIZIONE 54 Persone mediamente presenti
55 Ore fruizione nel giorno 56 Mesi fruizione nell'anno

INTERVENTI STRUTTURALI ESEGUITI
57 Interventi dopo la costruzione Si No 58 Anno
59 Ampliamenti
60 Variazioni di destinazione che hanno comportato incremento di carichi al singolo piano superiori al 20%
61 Interventi volti a trasformare l'edificio mediante insieme sistematico di opere che portino ad organismo diverso
62 Interventi strutturali in modifica o sostituzione di parti strutturali, con alterazione comportamento globale
63 Interventi di miglioramento/adeguamento sismico
64 Interventi di sola riparazione dei danni strutturali
65 Altro

EVENTI SUBITI DALLA STRUTTURA
66 Codice evento 67 Data / / 68 Tipo intervento
69 Codice evento 70 Data / / 71 Tipo intervento
72 Codice evento 73 Data / / 74 Tipo intervento

75 VERIFICA SISMICA Effettuata (cofinanziata da DPC) Effettuata (altri finanziamenti) Non effettuata

US 1

PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile

CONFERENZA DELLE REGIONI E DELLE PROVINCE AUTONOME

ANALISI DELLA CONDIZIONE LIMITE PER L'EMERGENZA (CLE) DELL'INSEDIAMENTO URBANO

UNITÀ STRUTTURALE
versione 2.0

Sezione 1 - IDENTIFICATIVI

Data compilazione / / Codice ISTAT

1 Regione
2 Provincia
3 Comune
4 Località abitata
5 Sezione censuaria
6 Identificativo Aggregato Strutturale
7 Identificativo Unità Strutturale
8 Identificativo Area di Emergenza
9 Identificativi infrastrutture di Accessibilità/Connessione a b c d
10 Indirizzo 11 Civico
12 Mappa in allegato (vedi retro)

Sezione 2 - CARATTERISTICHE GENERALI

POSIZIONE NELL'AGGREGATO 13 Isolata Sì No 14 Interna D'estremità D'angolo
15 FRONTE INTERFERENTE SU INFRASTRUTTURA ACCESSIBILITÀ/CONNESSIONE (H>L) O AREA DI EMERGENZA (H>d) Sì No
16 UNITÀ STRUTTURALE SPECIALISTICA Sì No 17 Chiesa Teatro Torre/campanile/ciminiera Altro
18 NUMERO PIANI TOTALI (INCLUSI INTERRATI) 19 PIANI INTERRATI 0 1 2 ≥3
20 ALTEZZA MEDIA DI PIANO (m) ≤2,50 2,50-3-50 3,50-5,00 ≥5,00 21 ALTEZZA ALL'IMPOSTA DELLA COPERTURA
22 VOLUME UNICO SU AC Sì No 23 SUPERFICIE MEDIA DI PIANO (mq)
24 STRUTTURA PORTANTE VERTICALE C.a. Acciaio Acciaio-c.l.s. Muratura Mista (muratura/c.a.) Legno Non identificata
25 TIPO MURATURA Buona Cattiva Non identificata 26 CORDOLI O CATENE Sì No
27 PILASTRI ISOLATI Sì No 28 PIANO PILOTIS Sì No 29 SOPRAELEVAZIONI Sì No
30 DANNO STRUTTURALE Gravissimo Medio - grave Leggero Assente 31 STATO MANUTENTIVO Carente Sufficiente Buono
PROPRIETÀ 32 Pubblica 33 Privata
34 MORFOLOGIA Pianeggiante Su leggero pendio (15°÷30°) Su forte pendio (>30°)
UBICAZIONE 35 Sotto versante incombente o forte pendio 36 Sopra versante incombente o cresta
MICROZONAZIONE SISMICA 37 Zona MS (condizione peggiore) Stabile Stabile con amplificazioni Instabile
Tipo instabilità 38 Frana 39 Liquefazione 40 Faglia attiva e capace 41 Cedimenti differenziali 42 Cavità sotterranee
GEOLOGIA / 46 IDROGEOLOGIA Localizzazione frana 43 Interferente con l'unità strutturale 44 A monte 45 A valle
Rischio PAI R1 R2 R3 R4 47 Area alluvionabile Sì No

Sezione 3 - CARATTERISTICHE SPECIFICHE

48 DESTINAZIONE D'USO (USO ATTUALE)
49 TIPO E NUMERO UNITÀ D'USO
A Residenziale (H) D Turistico (K) G Deposito (N)
B Commercio (I) E Produzione (L)
C Serv. pubbl. (J) F Uffici (M)
50 EPOCA DI COSTRUZIONE E RISTRUTTURAZIONE ≤1919 19-45 46-61 62-71 72-81 82-91 92-01 ≥2002
51 UTILIZZAZIONE >65% 30-65% <30% non utilizzato in costruzione non finito abbandonato
52 OCCUPANTI

ANNEX C: GNDT-II FILLED FORMS FOR CLE MASONRY BUILDINGS OF ANTIGUA EIXAMPLE, BARCELONA

VILLARROEL 233						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		D	45	1.00	45
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.5	67.5
		DIRECTION Y	D	45	1.5	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.25	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.5	12.5
6	PLAN CONFIGURATION		D	45	0.5	22.5
7	IN HEIGHT CONFIGURATION		A	0	0.5	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.5	0
10	NON STRUCTURAL ELEMENTS		A	0	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	1	25
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			63.89			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			63.89			

VILLARROEL 126-128						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	1.00	25
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			56.34			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			56.34			

VILLARROEL 127						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	C	25	1.50	37.5
		DIRECTION Y	D	45	0.75	33.75
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.25	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.25	0
10	NON STRUCTURAL ELEMENTS		A	0	1.00	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	0.00	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X				46.58		
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y				56.84		

VILLARROEL 231						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	C	25	1.50	37.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.25	0.25	0.0625
11	GENERAL MAINTENANCE CONDITIONS		C	1.00	1.00	1
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			56.84			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			46.58			

VILLARROEL 255-257						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		B	5	0.50	2.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.25	0.25	0.0625
11	GENERAL MAINTENANCE CONDITIONS		C	1.00	1.00	1
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			53.42			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			53.42			

VILLARROEL 134						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			56.84			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			56.84			

VILLARROEL 140						
#	**PARAMETER**		**CLASS**	**SCORE**	**WEIGHT**	**WEIGHTED SCORE**
1	**TYPE AND ORGANIZATION OF RESISTING SYSTEM**		**C**	**20**	**1.00**	**20**
2	**QUALITY OF RESISTING SYSTEM**		**C**	**25**	**0.25**	**6.25**
3	**CONVENTIONAL STRENGHT**	**DIRECTION X**	**D**	**45**	**1.50**	**67.5**
		DIRECTION Y	**D**	**45**	**1.50**	**67.5**
4	**BUILDING POSITION AND FOUNDATIONS**		**C**	**15**	**0.75**	**11.25**
5	**HORIZONTAL DIAPHRAGMS**		**C**	**25**	**0.50**	**12.5**
6	**PLAN CONFIGURATION**		**B**	**5**	**0.50**	**2.5**
7	**IN HEIGHT CONFIGURATION**		**A**	**0**	**0.50**	**0**
8	**CONNECTIONS AND CRITICAL ELEMENTS**		**D**	**45**	**0.25**	**11.25**
9	**LOW DUCTILITY ELEMENTS**		**A**	**0**	**0.00**	**0**
10	**NON STRUCTURAL ELEMENTS**		**A**	**0.00**	**0.25**	**0**
11	**GENERAL MAINTENANCE CONDITIONS**		**C**	**25.00**	**1.00**	**25**
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			53.42			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			53.42			

VILLARROEL 184						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		D	45	0.50	22.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.00	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X					60.26	
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y					60.26	

VILLARROEL 186						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25

VULNERABILITÀ NORMALIZZATA IN DIREZIONE X	56.84
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y	56.84

VILLARROEL 245						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X					56.84	
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y					56.84	

ANNEX D: GNDT-II FILLED FORMS FOR CLE MASONRY BUILDINGS OF ANTIGUA EIXAMPLE, BARCELONA AS AGGREGATES

VILLARROEL 233						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		D	45	1.00	45
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.5	67.5
		DIRECTION Y	D	45	1.5	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.25	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.5	12.5
6	PLAN CONFIGURATION		D	45	0.5	22.5
7	IN HEIGHT CONFIGURATION		A	0	0.5	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.5	0
10	NON STRUCTURAL ELEMENTS		A	0	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	1	25
12	INTERACTION IN ELEVATION		A	0	1.25	0
13	FLOOR PLANS INTERACTIONS		B	5	1.75	8.75
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			48.15			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			48.15			

VILLARROEL 126-128						
#	**PARAMETER**		**CLASS**	**SCORE**	**WEIGHT**	**WEIGHTED SCORE**
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	1.00	25
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		A	0	1.75	0
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			47.86			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			47.86			

VILLARROEL 127						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	C	25	1.50	37.5
		DIRECTION Y	D	45	0.75	33.75
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.25	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.25	0
10	NON STRUCTURAL ELEMENTS		A	0	1.00	0
11	GENERAL MAINTENANCE CONDITIONS		C	25	0.00	0
12	INTERACTION IN ELEVATION		D	45	1.25	56.25
13	FLOOR PLANS INTERACTIONS		C	15	1.75	26.25
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X				51.5		
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y				56.62		

VILLARROEL 231						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	C	25	1.50	37.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.25	0.25	0.0625
11	GENERAL MAINTENANCE CONDITIONS		C	1.00	1.00	1
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		B	5	1.75	8.75
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			49.36			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			44.23			

VILLARROEL 255-257						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		B	5	0.50	2.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.25	0.25	0.0625
11	GENERAL MAINTENANCE CONDITIONS		C	1.00	1.00	1
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		C	15	1.75	26.25
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			50.64			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			50.64			

VILLARROEL 134						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		A	0	1.75	0
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			47.86			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			47.86			

<table>
<tr><th colspan="7">VILLARROEL 140</th></tr>
<tr><th>#</th><th colspan="2">PARAMETER</th><th>CLASS</th><th>SCORE</th><th>WEIGHT</th><th>WEIGHTED SCORE</th></tr>
<tr><td>1</td><td colspan="2">TYPE AND ORGANIZATION OF RESISTING SYSTEM</td><td>C</td><td>20</td><td>1.00</td><td>20</td></tr>
<tr><td>2</td><td colspan="2">QUALITY OF RESISTING SYSTEM</td><td>C</td><td>25</td><td>0.25</td><td>6.25</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">CONVENTIONAL STRENGHT</td><td>DIRECTION X</td><td>D</td><td>45</td><td>1.50</td><td>67.5</td></tr>
<tr><td>DIRECTION Y</td><td>D</td><td>45</td><td>1.50</td><td>67.5</td></tr>
<tr><td>4</td><td colspan="2">BUILDING POSITION AND FOUNDATIONS</td><td>C</td><td>15</td><td>0.75</td><td>11.25</td></tr>
<tr><td>5</td><td colspan="2">HORIZONTAL DIAPHRAGMS</td><td>C</td><td>25</td><td>0.50</td><td>12.5</td></tr>
<tr><td>6</td><td colspan="2">PLAN CONFIGURATION</td><td>B</td><td>5</td><td>0.50</td><td>2.5</td></tr>
<tr><td>7</td><td colspan="2">IN HEIGHT CONFIGURATION</td><td>A</td><td>0</td><td>0.50</td><td>0</td></tr>
<tr><td>8</td><td colspan="2">CONNECTIONS AND CRITICAL ELEMENTS</td><td>D</td><td>45</td><td>0.25</td><td>11.25</td></tr>
<tr><td>9</td><td colspan="2">LOW DUCTILITY ELEMENTS</td><td>A</td><td>0</td><td>0.00</td><td>0</td></tr>
<tr><td>10</td><td colspan="2">NON STRUCTURAL ELEMENTS</td><td>A</td><td>0.00</td><td>0.25</td><td>0</td></tr>
<tr><td>11</td><td colspan="2">GENERAL MAINTENANCE CONDITIONS</td><td>C</td><td>25.00</td><td>1.00</td><td>25</td></tr>
<tr><td>12</td><td colspan="2">INTERACTION IN ELEVATION</td><td>C</td><td>25</td><td>1.25</td><td>31.25</td></tr>
<tr><td>13</td><td colspan="2">FLOOR PLANS INTERACTIONS</td><td>A</td><td>0</td><td>1.75</td><td>0</td></tr>
<tr><td>14</td><td colspan="2">PRESENCE OF OFFSET CEILINGS</td><td>D</td><td>45</td><td>0.75</td><td>33.75</td></tr>
<tr><td>15</td><td colspan="2">STRUCTURA L OF TYPOLOGICAL HETEROGENEITY</td><td>C</td><td>20</td><td>1.5</td><td>30</td></tr>
<tr><td>16</td><td colspan="2">PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES</td><td>B</td><td>15</td><td>1.25</td><td>18.75</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td colspan="3">VULNERABILITÀ NORMALIZZATA IN DIREZIONE X</td><td colspan="4">46.15</td></tr>
<tr><td colspan="3">VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y</td><td colspan="4">46.15</td></tr>
</table>

VILLARROEL 184						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		D	45	0.50	22.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.00	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		A	0	1.75	0
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X					49.57	
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y					49.57	

VILLARROEL 186						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
12	INTERACTION IN ELEVATION		C	25	1.25	31.25
13	FLOOR PLANS INTERACTIONS		C	15	1.75	26.25
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X					52.35	
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y					52.35	

VILLARROEL 245						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		C	20	1.00	20
2	QUALITY OF RESISTING SYSTEM		C	25	0.25	6.25
3	CONVENTIONAL STRENGHT	DIRECTION X	D	45	1.50	67.5
		DIRECTION Y	D	45	1.50	67.5
4	BUILDING POSITION AND FOUNDATIONS		C	15	0.75	11.25
5	HORIZONTAL DIAPHRAGMS		C	25	0.50	12.5
6	PLAN CONFIGURATION		C	25	0.50	12.5
7	IN HEIGHT CONFIGURATION		A	0	0.50	0
8	CONNECTIONS AND CRITICAL ELEMENTS		D	45	0.25	11.25
9	LOW DUCTILITY ELEMENTS		A	0	0.00	0
10	NON STRUCTURAL ELEMENTS		A	0.00	0.25	0
11	GENERAL MAINTENANCE CONDITIONS		C	25.00	1.00	25
12	INTERACTION IN ELEVATION		D	45	1.25	56.26
13	FLOOR PLANS INTERACTIONS		C	15	1.75	26.25
14	PRESENCE OF OFFSET CEILINGS		D	45	0.75	33.75
15	STRUCTURA L OF TYPOLOGICAL HETEROGENEITY		C	20	1.5	30
16	PERCENTAGE DIFFERENCE OF OPENING AREAS AMONG ADJACENT FACADES		B	15	1.25	18.75
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X					56.62	
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y					61.75	

ANNEX E: GNDT-II FILLED FORMS FOR CLE RC BUILDINGS OF ANTIGUA EIXAMPLE, BARCELONA

VILLARROEL 114						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			57.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			

VILLARROEL 121-123						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		C	2	1	2
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			60			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			60			

VILLARROEL 130-132						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	B	0	1	0
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			55			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			55			

VILLARROEL 137-139						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		A	0	1	0
7	IN HEIGHT CONFIGURATION		B	1	2	2
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			40			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			40			

VILLARROEL 138						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		C	2	1	2
7	IN HEIGHT CONFIGURATION		B	1	2	2
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			45			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			45			

VILLARROEL 141						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		B	1	2	2
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			40			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			40			

VILLARROEL 165						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			57.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			

VILLARROEL 167						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			57.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			55			

VILLARROEL 171						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	B	0	1	0
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		B	1	2	2
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			42.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			42.5			

VILLARROEL 172-174						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			55			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			52.5			

VILLARROEL 181						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			52.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			52.5			

VILLARROEL 187						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			57.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			

VILLARROEL 191						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			57.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			

VILLARROEL 197						
#	**PARAMETER**		**CLASS**	**SCORE**	**WEIGHT**	**WEIGHTED SCORE**
1	**TYPE AND ORGANIZATION OF RESISTING SYSTEM**		**A**	**0**	**4**	**0**
2	**QUALITY OF RESISTING SYSTEM**		**B**	**1**	**1**	**1**
3	**CONVENTIONAL STRENGHT**	**DIRECTION X**	**C**	**1**	**1**	**1**
		DIRECTION Y	**A**	**-1**	**1**	**-1**
4	**BUILDING POSITION AND FOUNDATIONS**		**B**	**1**	**1**	**1**
5	**HORIZONTAL DIAPHRAGMS**		**A**	**0**	**1**	**0**
6	**PLAN CONFIGURATION**		**B**	**1**	**1**	**1**
7	**IN HEIGHT CONFIGURATION**		**C**	**3**	**2**	**6**
8	**CONNECTIONS AND CRITICAL ELEMENTS**		**B**	**1**	**1**	**1**
9	**LOW DUCTILITY ELEMENTS**		**B**	**1**	**1**	**1**
10	**NON STRUCTURAL ELEMENTS**		**B**	**1**	**1**	**1**
11	**GENERAL MAINTENANCE CONDITIONS**		**A**	**0**	**2**	**0**
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			**45**			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			**40**			

VILLARROEL 200						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		A	0	1	0
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			52.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			50			

#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
VILLARROEL 205-219						
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		A	0	4	0
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		A	0	1	0
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			37.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			37.5			

VILLARROEL 208-214						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	B	0	1	0
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			55			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			55			

VILLARROEL 220-222						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		C	2	1	2
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			60			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			

VILLARROEL 223						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	A	-1	1	-1
		DIRECTION Y	A	-1	1	-1
4	BUILDING POSITION AND FOUNDATIONS		A	0	1	0
5	HORIZONTAL DIAPHRAGMS		A	0	1	0
6	PLAN CONFIGURATION		B	1	1	1
7	IN HEIGHT CONFIGURATION		B	1	2	2
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			37.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			37.5			

VILLARROEL 253						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		A	0	4	0
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	B	0	1	0
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		A	0	1	0
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			42.5			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			42.5			

VILLARROEL 162-164						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	C	1	1	1
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		A	0	1	0
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			55			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			55			

VILLARROEL 235-237						
#	PARAMETER		CLASS	SCORE	WEIGHT	WEIGHTED SCORE
1	TYPE AND ORGANIZATION OF RESISTING SYSTEM		B	1	4	4
2	QUALITY OF RESISTING SYSTEM		B	1	1	1
3	CONVENTIONAL STRENGHT	DIRECTION X	C	1	1	1
		DIRECTION Y	B	0	1	0
4	BUILDING POSITION AND FOUNDATIONS		B	1	1	1
5	HORIZONTAL DIAPHRAGMS		B	1	1	1
6	PLAN CONFIGURATION		C	2	1	2
7	IN HEIGHT CONFIGURATION		C	3	2	6
8	CONNECTIONS AND CRITICAL ELEMENTS		B	1	1	1
9	LOW DUCTILITY ELEMENTS		B	1	1	1
10	NON STRUCTURAL ELEMENTS		B	1	1	1
11	GENERAL MAINTENANCE CONDITIONS		A	0	2	0
VULNERABILITÀ NORMALIZZATA IN DIREZIONE X			60			
VULNERABILITÀ NORMALIZZATA IN DIREZIONE Y			57.5			